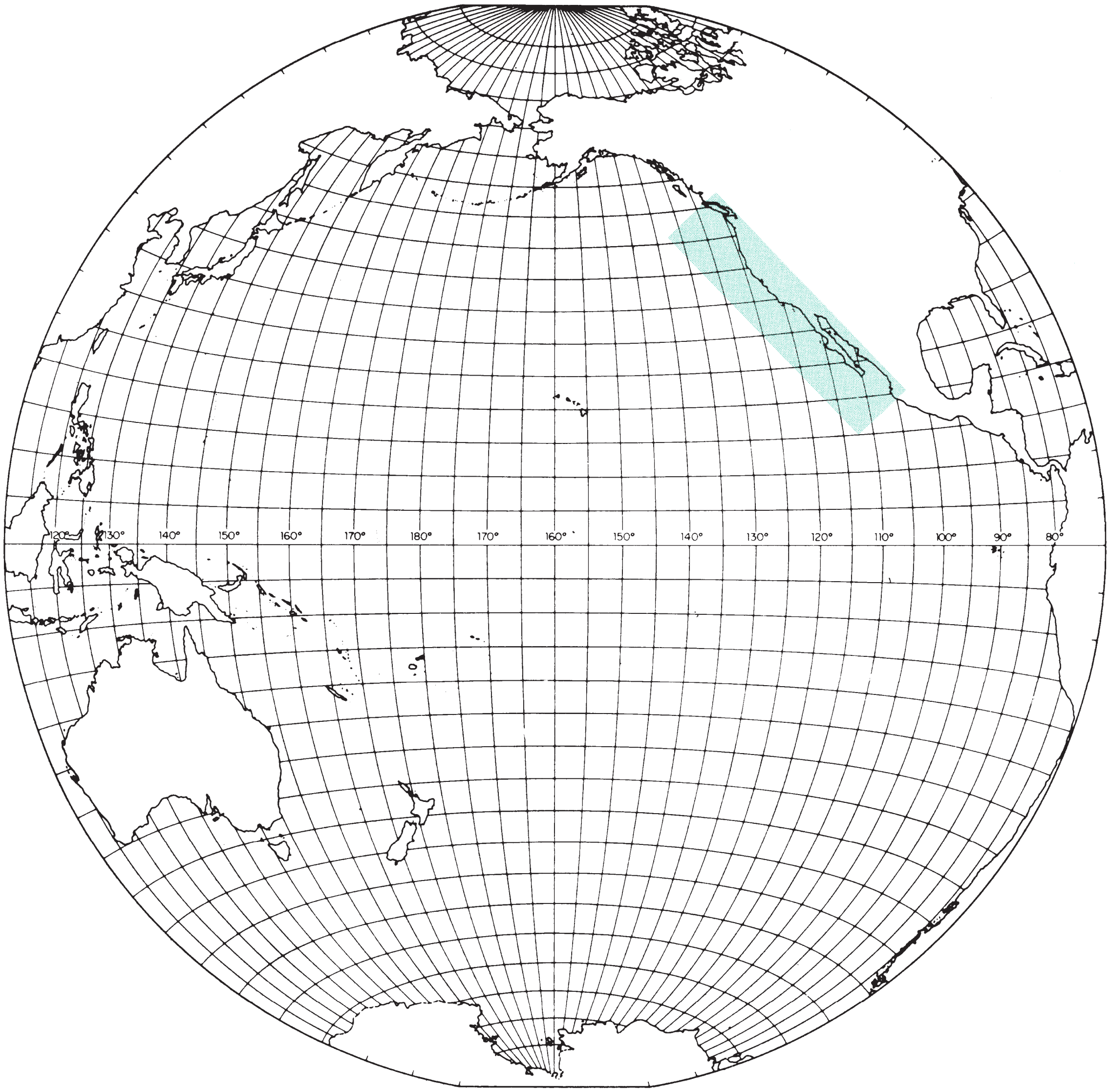

California Cooperative Oceanic Fisheries Investigations

Reports

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Part I

REPORTS, REVIEW, AND PUBLICATIONS

REPORT OF THE CALCOFI COMMITTEE 2008

CDFG HIGHLIGHTS

Marine Life Protection Act Project

The Marine Life Protection Act mandates the reexamination and redesign of a network of Marine Protected Areas (MPAs) for the state of California. The Act is being implemented in five planning regions encompassing the California coastline, including San Francisco Bay, and is expected to be completely implemented by 2011. The planning process includes input from a broad-based Regional Stakeholder Group (RSG) in each planning region and oversight by a Blue Ribbon Task Force (BRTF) appointed by the Secretary for Resources and the California Fish and Game Commission (Commission), the final decision-making body in the process. The first planning region was the Central Coast study region—Pigeon Point in San Mateo County southward to Point Conception in Santa Barbara County. Planning for this region was completed in April 2007.

Planning for the second region, the North Central Coast study region—from Pigeon Point, north to Alder Creek, near Point Arena, Mendocino County—commenced in the summer of 2007. The BRTF crafted an Integrated Preferred Alternative (IPA) in April 2008 by incorporating ideas from all three final proposals generated by the North Central Coast RSG. In October 2008, the Commission identified the IPA as its preferred alternative for regulatory review. The Commission is currently considering adopting MPAs proposed for the North Central Coast study region, expected to occur in late summer 2009.

The third planning region is the South Coast study region—from the U.S.-Mexico international border, north to Point Conception. Planning for this region commenced in the summer of 2008 and is ongoing. Final recommendations from the BRTF on MPAs proposed for the South Coast study region will be presented to the Commission in November 2009. See www.dfg.ca.gov/mlpa for more information.

State Finfish Management Project

The State Finfish Management Project manages recreational and commercial finfish regulated by the State of California. Species examined within this project reside primarily in nearshore habitats but may range throughout state waters. Included in these species are California halibut (*Paralichthys californicus*). Project staff completed fishery-independent trawl surveys and collaborated with commercial fishers to collect data on California halibut for an upcoming stock assessment to begin January 2009. Staff worked on a commercial fishing vessel to tag sub-legal halibut and collect growth and mortality information. These data, coupled with sampling by the commercial California halibut fishery and historical survey information, will be used in the statewide assessment.

The Project also began a hooking mortality study of California halibut in San Francisco Bay. This study was undertaken in part due to concerns about unusually high recreational and commercial fishing effort and catch in 2008, potentially as a result of the ocean salmon fishery closure. Average catch rates were around one legal halibut per recreational boat angler during the summer. Project staff monitored and sampled the recreational skiff fishery during this period, supplementing efforts by the California Recreational Fisheries Survey (CRFS).

In 2008, the Pacific hagfish (*Eptatretus stoutii*) commercial fishery continued its resurgence. Landings exceeded 1.5 million pounds in California for the second consecutive year after a 17-year period of low landings. Primary ports for hagfish landings were Eureka, Morro Bay, Los Angeles, and San Diego. The Project continued to track fishery landings statewide and sampled the fishery for size composition.

Recreational Fisheries

CRFS began in January 2004 to provide catch and effort estimates for marine recreational finfish fisheries. This survey is an updated version of the Marine Recreational Finfish Fisheries Statistical Survey (MRFSS), which started in 1980. CRFS generates monthly estimates of total recreational finfish catch for four fishing modes (private and rental boats, beaches and banks, manmade structures such as piers, and commercial passenger fishing vessels) within six geographic regions along California's coast. These data are used by state and federal regulators to draft regulations to protect fish stocks and provide recreational fishing opportunities.

CRFS incorporates field sampling and telephone surveys. In 2008, approximately 45 samplers worked statewide to gather field-sampling data. CRFS samplers interviewed more than 61,400 anglers at more than 400 sites, and examined nearly 190,000 fish. In addition, the telephone survey conducted nearly 26,000 interviews with licensed anglers in 2008.

In 2008, the CRFS program started two pilot studies to improve current sampling methodology. The first study examined methods of determining catch and effort for anglers returning from private marinas, moorings, and docks that CRFS field samplers cannot access. This study used field-based counts of the number of recreational fishing boats that return from seven southern California marinas to generate monthly estimates of private-access fishing effort. The estimates will be compared to current estimates generated from the licensed angler telephone survey. The second study, the Saltwater Angler Logbook Study, works with volunteers from both public and private access sites to compare catch and discard rates between the two groups. The study will compare public and private fishers to better refine methods for estimating catch and effort. For more information: http://www.dfg.ca.gov/marine/crfs.asp

Fishery-Independent SCUBA Assessment Project

This project is a collaborative marine research and monitoring program that works with other agencies and academic institutions to conduct surveys of fishes and invertebrates in nearshore subtidal habitats. In southern California, the project is working on surfperch and other nearshore sandy beach fishes using beach seining and mark-recapture methods. Data are being collected on the movement patterns of barred sand bass (*Paralabrax nebulifer*) in relation to their spawning behavior.

In central California, the abundance, mortality, and movement patterns of rocky reef fishes listed in CDFG's Nearshore Fishery Management Plan are being investigated using trapping, hook-and-line, and mark/recapture methods. Estimates of the age, growth, and size at maturity of kelp greenling (*Hexagrammos decagrammus*) are also being investigated using SCUBA surveys.

Ocean Salmon Project

In 2008, counts of Sacramento River Fall Chinook (SRFC) salmon (*Oncorhynchus tshawytscha*) returning to spawn in the Central Valley were the lowest (66,200 salmon) in the 40-year record of escapement surveys. This was also the second consecutive year that SRFC failed to meet the Fishery Management Plan conservation objective of at least 122,000 adult spawners. Due to this decline, California Department of Fish and Game (Department) staff on the Pacific Fisheries Management Council's Salmon Technical Team developed a new Sacramento Index model which examined the ocean harvest of SRFC along the West Coast. This model was a significant improvement over the Central Valley Index, which only used the ocean harvest south of Point Reyes and included all Central Valley salmon stock runs (fall, late-fall, winter, and spring). Using the Sacramento Index, only 122,200 SRFC adults are forecasted to remain in the ocean during the 2009 season.

The Commission and Pacific Fishery Management Council voted to continue the closure of all commercial and recreational Chinook salmon fishing in state and federal ocean waters south of Cape Falcon, Oregon. SRFC generally account for 80%–95% of the ocean salmon catch off California. One exception to this closure will be a 10-day recreational salmon fishery (29 August through 7 September 2009) in the waters north of Horse Mountain to the California/Oregon border designed to target the more abundant Klamath River Fall Chinook. In addition, the Department recommended that all river fishing for Chinook salmon within the Central Valley be closed during 2009 except for a 16 November–31 December fishery in the upper Sacramento River designed to target late-fall run Chinook.

Invertebrate Fisheries Management Project

Invertebrate Fisheries Project biologists completed a number of studies working primarily with spiny lobster (*Panulirus interruptus*), abalone (*Haliotis* spp.), Dungeness crab (*Cancer magister*) and a variety of bivalves. A spiny lobster study comparing different hoop-net designs was submitted to the *Fish and Game* journal. The study showed that newer rigid-style hoop nets have increased catch efficiencies over traditional hoop nets, thereby potentially increasing the recreational catch.

Department staff also completed a report of recreational lobster fishing activity summarizing surveys conducted with recreational fishers in 2007 and submitted this to the Ocean Protection Council. In addition, Project staff received funding approval for a joint study with San Diego State on lobster movement patterns within San Diego Bay to begin in 2009. Staff biologists completed a lobster biology informational leaflet, in cooperation with California Sea Grant, which was available prior to the new lobster report card released in 2008. In conjunction with the California Lobster and Trap Fishery Association, Project staff planned a new at-sea logbook sampling program patterned after the New Zealand Voluntary Logbook program for the 2009 lobster season.

Abalone stock assessment work continued in both the northern California recreational fishery and southern California recovery region. Southern California staff completed a three-year red abalone (*Haliotis rufescens*) stock assessment at San Miguel Island in cooperation with the California Abalone Association (former commercial abalone divers). Staff continued to work with the Abalone Advisory Group (AAG), an advisory group established to make recommendations on a potential San Miguel Island abalone fishery. Project staff, the AAG, and a Technical Panel of the AAG are working together to develop stock estimates and potential total allowable catch harvest scenarios to present to the Commission. Two studies were completed with red abalone from San Miguel Island to help inform this process, one examining gamete production and another looking at temperature and the onset of withering syndrome, a lethal abalone disease. A red abalone tagging study was also initiated at San Miguel Island with the former commercial abalone divers to study growth and movement patterns.

In northern California, a five-year field study assessing densities and size structure of the population at fishery index stations was completed and is being prepared for presentation to the Commission. Since 2000, abalone recruitment has been monitored within abalone recruitment modules annually while female gonad index is examined quarterly at Van Damme State Park. An abalone fishing information pamphlet was completed in collaboration with Sea Grant presenting the results of abalone research on population dynamics and importance of the existing 7 inch minimum size limit.

In 2008, a new site in Humboldt Bay was added to the Dungeness crab megalopae trapping study. This study quantifies crab recruitment in an effort to establish an index which can be used to predict the strength of the crab fishery in four years (when the megalopae grow to legal size). Dungeness megalopae trapping is also being conducted in Bodega Bay and southern Oregon in order to examine spatial as well as temporal patterns in recruitment. Department staff also worked to establish a new Dungeness Crab Task Force to discuss commercial crab management issues.

Staff resumed both fishery-dependent and independent assessments of marine bivalves along the coast. Gaper clam and razor clam fisheries in Humboldt County were assessed using both creel surveys of fishers as well as fishery-independent transect surveys. Pismo clam densities were surveyed along beaches in central and southern California to compare with previous surveys and assess current population levels.

SIO HIGHLIGHTS

Scripps Institution of Oceanography successfully completed the CalCOFI summer and fall cruises in 2008, and the winter and spring cruises in 2009. The spring 2009 cruise suffered from bad weather which prevented us from completing stations along line 77. The California Current Ecosystem-Long Term Ecological Research (CCE-LTER) group participated on all four cruises and augmented CalCOFI sampling with measurements aimed at characterizing biogeochemical cycling and lower trophic level community structure in more detail. During the winter cruise the CCE-LTER group tested an advanced laser fluorescence system on loan from Alexander Chekalyuk for the continuous characterization of phytoplankton community structure and physiological state. The system performed extremely well, revealing small-scale structure in the community that is impossible to detect using individual stations. It is hoped that funding for the purchase of such an instrument can be obtained in the near future. The CCE-LTER group lost their laser optical plankton counter when the hydro wire broke. The marine mammal program participated on all four cruises as well, using visual observers and acoustic methods to enumerate the abundance of marine mammals on station and along the cruise tracks. The seabird program continues to be plagued by funding constraints and was only able to participate on the spring and summer cruise.

Conditions in the CalCOFI survey area in 2008 continued to be consistent with patterns observed since 1999, when the California Current entered a cool Pacific Decadal Oscillation (PDO) phase. Mixed-layer temperature anomalies suggest that La Niña conditions continued to affect the area during 2008; during 2009 conditions had returned to normal. Nitracline depth continued to be relatively shallow, about 10 m shallower than the long-term mean, and nitrate concentration continued to be higher than average. Although phytoplankton concentrations have exhibited a positive trend since 1984 in the CalCOFI survey area, concentrations in 2008 appeared close to the long-term mean. Zooplankton displacement volume followed the pattern of relatively low mean concentrations observed since about 1993; concentrations even in spring and fall have not increased notably from the low values observed through the winter.

A five-frequency (18, 38, 70, 120, and 200 kHz) Simrad EK-60 system was operated for the first time on RV *New Horizon* during the January 2009 CalCOFI cruise to examine the distribution and abundance of mid-trophic levels (krill, micronekton, and small pelagics) in relation to hydrographic features and their predators and prey.

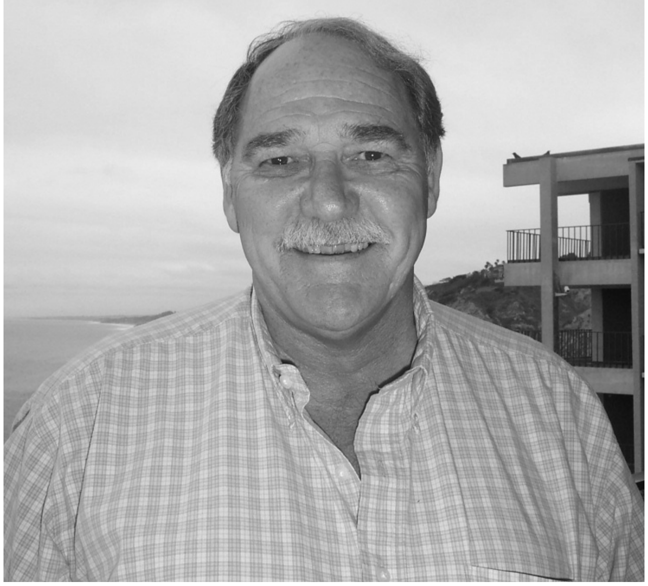
For the past year, the California Conservancy Ocean Protection Council has funded re-sorting of historical CalCOFI samples to enumerate phyllosoma of the spiny lobster. A time series of the abundance of the early-stage larvae should provide a proxy time series for the abundance of the spawning stock extending back 60 years, which will contribute to the management of this valuable fishery as well as to understanding how the population responds to climatic forcing. The funding also enabled historical ichthyoplankton data sets from CalCOFI, the Los Angeles County Museum, and coastal power plant monitoring to be brought together in a database. The data are now being analyzed to provide baseline data on these communities prior to establishment of marine protected areas along the California coast. CalCOFI data sets are also being made available through a publicly-available website as part of this project.

There were several research developments this past year based on the CalCOFI data. Declining oxygen concentrations in the California Current have been a source of major concern, with hypoxia on the Oregon shelf potentially having major impacts on demersal fisheries (Chan et al. 2008). Analysis of the CalCOFI oxygen time series indicates a declining trend in oxygen concentration in much of the Southern California Bight since 1984 (Bograd et al. 2008). However, a more recent analysis extending back to 1949 indicates that low oxygen concentrations were observed along the coast in the 1950s as well, raising the question as to whether the recent hypoxia may be part of a longer-term cycle (McClatchie et al. this volume). The causes of these changes in oxygen concentration remain unclear. Potential mechanisms include declining concentrations of oxygen in the California Undercurrent whose source waters are the eastern tropical Pacific Ocean and decreasing depths of isopycnals driven by large-scale wind patterns as reflected in the North Pacific Gyre Oscillation (NPGO). Increasing rates of primary productivity, that are driving such trends off Oregon, are a less likely cause in the Southern California Bight.

CalCOFI research this year also includes the development of the NPGO index (Di Lorenzo et al. 2008). Previous climate indices, such as the PDO and ENSO indices were not well correlated with variability patterns of salinity, nutrients, chlorophyll and key fish stocks, such as Pacific sardine (*Sardinops sagax*), in the CalCOFI time series. However, the NPGO is based on regional and basin-scale variations in wind-driven upwelling and horizontal advection, which are the fundamental processes controlling salinity and nutrient concentrations, and this index appears well-correlated with these key variables. In an independent but related development, Rykaczewski and Checkley 2008 showed that offshore, wind-stress curl-driven upwelling, which is linked to the NPGO, is closely correlated with surplus production of the Pacific sardine population.

NOAA HIGHLIGHTS

CalCOFI Legend Retires



For the past 35 years Richard Charter, Supervisory Computer Specialist, has had a central role in the scientific mission of the Fisheries Resources Division at the Southwest Fisheries Science Center and has made crucial contributions to virtually all the scientific research of the Division. He excelled in data base design and management, survey cruise design and ship operations, and in the management of the laboratory's plankton sorting laboratory.

Since 1978, Rich has been responsible for planning and monitoring the CalCOFI survey cruises, developing and implementing shipboard and laboratory equipment and computer systems, and establishing and managing the computer databases for the CalCOFI time series. Rich embodies the spirit of CalCOFI. He is always cheerful, constructive, and generous. He is philosophical, providing such advice as, "Don't put anything over the side you're not prepared to lose," and only angry at the important things, like the loss of a sea day. Rich brought CalCOFI into the computer age and his comprehensive knowledge of the databases he established was essential to the scientific advances of the program.

The CalCOFI fish-egg and larval time series has become increasingly important as a fishery-independent measure of changes in key fishery stocks and is used constantly by scientists and managers to assess stocks and set harvest guidelines. One of Rich's long-term accomplishments was making this data accessible. He was intensely involved in developing several web sites that present the data in uncomplicated ways with links to the deeper data strata. He also developed innovative graphical methods to communicate and interpret the time series, and created an open environment where the software is free for programmers to update it and each other's capabilities through frequent communication. Rich kept everyone up to date on cruise operations and key results by generating computer maps almost in real time.

In addition, Rich supervised the processing, sorting, and archiving of plankton net and trawl samples for the Fisheries Resources Division. For CalCOFI plankton samples this involves separating fish larvae and eggs from zooplankton, identifying and enumerating key fishery species, and transferring the zooplankton samples to SIO. One of his many accomplishments has been to develop a system of data entry forms and computer programs that allow rapid and efficient archiving of data as the samples are sorted. As a result, important data needed for fisheries management decisions are made available within weeks, sometimes days, after the completion of a survey cruise. Rich shared this system with other sorting center managers and it has been adopted by numerous laboratories in the U.S. and internationally.

Rich will be sorely missed, and on behalf of the CalCOFI community, we thank him for his years of tireless effort and numerous achievements. Congratulations on a well deserved retirement.

New Addition

We would like to extend a warm welcome to Dr. Ed Weber, the newest CalCOFI data manager at SWFSC. Ed has been a postdoctoral research scientist in the Fisheries Oceanography lab for the past year. He received his Ph.D. from Colorado State University, and has previously worked for Versar, Inc., the U.S. Bureau of Reclamation, and the U.S. Fish and Wildlife Service. Ed brings considerable knowledge to the position and we look forward to working with him for many years to come.

California Current Ecosystem Surveys

In 2008 the Fisheries Resources Division of the Southwest Fisheries Science Center conducted two coast-wide California Current Ecosystem (CCE) Surveys of the U.S. West Coast. These cruises were an expansion of the basic CalCOFI approach. The first ran in April 2008 using the NOAA RVs *David Starr Jordan* and *Miller Freeman*. A second survey was conducted in July/August on the *David Starr Jordan*.

The surveys were conducted in an abnormally cold year, strongly influenced by La Niña conditions during the spring spawning season of the Pacific sardine. Spawning of sardine was only observed south of San Francisco and was concentrated south of 35ºN, with strong indication of spawning extending south of the U.S.-Mexico border in waters that were not surveyed. No Pacific sardine spawning was observed in July/August except at the most southerly station. No evidence was found for spawning of Pacific sardine in northern California, Oregon, or Washington during these surveys.

Acoustic data provided a wealth of information on the distribution of larger plankton and fish that is relevant to assess forage for predators such as seabirds, but were of limited utility for biomass estimation of small pelagic fish. This was due to an unquantifiable contribution to "fish backscatter" from mesopelagic fish and zooplankton. The survey results highlight the need for better acoustic target identification, which is currently being addressed with a new towed stereo camera.

Trawling results indicated that cooler surface temperatures might have affected the movement of Pacific sardine. Compared to a previous coast-wide survey in 2006, sardines were larger in the southern area in 2008, a result that is consistent with delayed or restricted northern movement of sardine. Jack mackerel (*Trachurus symmetricus*), Pacific mackerel (*Scomber australasicus*), and Pacific sardine were absent from research trawl catches in the northern part of the survey in April 2008, but were caught south of 35°N. Pacific sardine were caught at inshore stations in the northern area in July/August. Northern anchovy (*Engraulis mordax*) were caught in both northern and southern areas in both seasons. Unfortunately, trawling was restricted south of San Francisco due to gear problems in July/August, which compromised results.

Seabird counts indicated a seasonal shift in dominant species, which is a result confirming previously published findings. Primarily piscivorous birds constituted 37% of the counts in April compared to 72% in July/August. Planktivorous seabirds such as the northward migrating red phalarope (*Phalaropus fulicarius*) dominated counts in April, followed by the common murre (*Uria aalge*) that consume both plankton and small pelagic fish. In contrast, the most abundant species in July/August were summer-resident sooty shearwaters (*Puffinus griseus*) that are more piscivorous, again followed by common murres.

A NOAA Technical Memorandum was published that summarizes the preliminary results from both surveys (McClatchie 2009).

CalCOFI Cruises

It was a busy field season for CalCOFI's 59th year and a great deal was accomplished. In addition to completing the standard quarterly surveys, back-to-back coast-wide surveys were achieved during the spring and summer months. Over the course of the 2008 calendar year a total of six individual surveys were completed using three different vessels: SIO's RV *New Horizon*, and the NOAA RVs *David Starr Jordan* and *Miller Freeman*. Throughout these surveys a total of 471 Bongo tows, 456 Pairovet tows, 442 Manta tows, 496 CTD casts, 3225 CUFES samples and approximately 3200 hours of acoustical data were collected during the field season. In addition, 140 surface trawls were conducted netting approximately 2700 kilograms of adult and juvenile Pacific sardine for the annual spawning biomass estimate. Sea surface temperature anomalies for 2008 were generally negative for the entire U.S. West Coast although the Southern California Bight did exhibit some neutral and positive anomalies during spring and summer months.

In turn, the Pacific sardine spawning distribution was limited to the offshore portion of the bight and egg densities were generally lower than past surveys.

The 2008 field season saw the welcome addition of new personnel joining the CalCOFI group at SIO as Dave Faber and Grant Susner came on board in mid-season. Their experience and expertise will benefit the entire CalCOFI program.

CalCOFI Ichthyoplankton Update

The SWFSC Ichthyoplankton Ecology group projects to update larval fish identifications to current standards from 1951 to the present, and to re-identify the fish eggs collected in the CalCOFI bongo net samples to add count data for eggs of Pacific whiting (hake, *Merluccius productus*) and jack and Pacific mackerels to the database, continued this year. We have completed egg re-identifications from 1988 to the present and currently are updating larval identifications for samples collected in 1968.

During 2008 overall larval fish abundance increased slightly compared with 2007. Northern anchovy larvae abundance increased by an order of magnitude in abundance compared with 2007, but remained well below the recent 2005 peak abundance. Pacific sardine abundance also increased, but only slightly, in 2008 compared with 2007, and like anchovy remained well below the most recent peak (in 2005) of larval abundance. Ichthyoplankton data suggest that the region of peak sardine spawning began to shift southward from central California in 2005, and in 2008 the peak spawning area was again off southern California.

Review of Rockfish

Recent genetic studies at Southwest Fisheries Science Center have revealed that the heavily exploited vermilion rockfish, *Sebastes miniatus*, is really a cryptic species pair. The splitting of this species affects stock size estimates and draws attention to the unintended consequences of depth-based management policies. Distinct differences in exploitation levels of the two species necessitated an evaluation of population structure and connectivity among regional management segments of the fishery.

Staff from the Fisheries Resources Division analyzed gene flow between populations and calculated larval dispersal values using 782 bp of DNA sequence data from the mitochondrial cytochrome *b* gene of 681 vermilion rockfish sampled from 16 sites between Kyuquot Sound, Canada and San Quintin, Mexico. Significant genetic heterogeneity was found among sample sites (FST = 0.0742, $p < 0.001$). Isolation by distance analysis produced a strong and significant correlation, suggesting that average larval dispersal distance is on the order of 10s of kilometers (Hyde and Vetter, in press).

Analysis of molecular variance showed strong and significant partitioning of genetic variance across the biogeographic boundary at Point Conception (FCT = 0.0923, $p < 0.001$). Additional genetic barriers were found across Cape Mendocino, Punta Colnett, Santa Monica Bay, and along the coast of Washington. These genetic barriers conform to oceanographic compartments previously proposed for the California Current ecological geography province and suggest natural management units for this species at Cape Mendocino and Point Conception.

Larval Production Biomass Estimate of Bocaccio

The size of the bocaccio (*Sebastes paucispinis*) stock in the Southern California Bight was estimated based on catches of larvae in the 2002 and 2003 CalCOFI and CCA-enhanced ichthyoplankton surveys. Area-weighted total length compositions of pre-flexion larvae in each of the two years were determined from survey data and year-specific larval length-to-age transition matrices were estimated from counts of daily otolith increments. Together these results were used to estimate the daily rates of larval production and mortality during the two years, which were expanded to annual production rates with knowledge of the spawning season, estimated from the long-term (1950–2005) time series of larval abundance in all CalCOFI surveys. Total annual larval production was then translated to total spawning biomass by estimating the population weight-specific fecundity of females, derived from a length-based life table analysis of adult reproductive parameters (maturity, fecundity, and spawning frequency) and estimates of the length composition of the southern California stock of bocaccio in 2002 and 2003. The adult reproductive parameters were estimated from ovary samples collected during the 2003 spawning season in Ensenada, Mexico, whereas the length composition of the stock was estimated from a restricted, Southern California Bight stock assessment model that was based on MacCall 2005.

Results indicate that in 2002 there were 3470 mt of female spawning biomass in the Southern California Bight or, equivalently, 6953 mt of total biomass (males and females $\geq$ 16 cm FL). Similarly, in 2003 there were 5921 mt of female spawning biomass and 10,656 mt of total biomass (Ralston and MacFarlane, in review). Differences in these estimates are due in part to the growth and maturation of a very strong 1999 year class and in part to measurement error. The estimates, evaluated by jackknife re-sampling and application of the Delta Method, are shown to be relatively precise. The biomass estimates also agree well with the restricted southern area model.

PaCOOS—Pacific Coast Ocean Observing System

In 2008, the focus for PaCOOS was to improve data access and interoperability as well as new observations in support of the California Current (CC) ecological observing system. Data management activities centered on access of NOAA's West Coast biological and physical data in partnership with academics. With funds from the NOAA IOOS Program, the Cooperative Zooplankton Dataspace (http://oceaninformatics.ucsd.edu/zooplankton/) was developed and provides queriable interfaces to zooplankton and euphausiid data. In addition, three existing data portals were updated with quality assured and quality controlled data and are accessible via the PaCOOS website (www.pacoos.org) as well as through the following home servers:

1. NOAA Habitat data:
   http://tomcat.coas.oregonstate.edu/
2. NOAA Pelagic data:
   http://oceanwatch.pfeg.noaa.gov/PaCOOS/
3. National Marine Sanctuary physical data:
   http://portal.ncddc.noaa.gov/wco/

Through leveraging of PaCOOS funds with CalCOFI and California Ocean Protection Council and CCE-LTER Programs at SIO, the historical CalCOFI physical and biological data are migrating to the web (http://oceaninformatics.ucsd.edu/datazoo/).

Data access and data interoperability underlie ecological forecasts and assessments in the California Current. Both the continued closure of the California salmon fishery in 2008 and the discussions at the Pacific Fisheries Management Council (PFMC) on the influence of ocean conditions on salmon survival demonstrate a growing need for PaCOOS and others to develop these assessment products.

Collaboration and partnerships within NOAA and between NOAA and academic scientists remains the primary means of developing ocean surveys. The effort by NOAA/NWFSC and Oregon State University at Newport Oregon is the longest-running ocean survey program in the northern California Current, established in 1996. A second effort was established in 2008 off Trinidad Head as a collaboration between NOAA/SWFSC and Humboldt State University. A third ocean survey line began in the fall of 2008, off Bodega Bay. This new line is operated by the Bodega Marine Lab of the University of California, Davis with funds from the Sonoma County Water Agency. Each of these two new lines is patterned after the Newport Line hydrographic and plankton survey. An ecological forecast is also under development between the SWFSC and SIO with funds from the NOAA IOOS Program. This project utilizes existing SIO climate model outputs (temperature, salinity with depth, sea surface height, and currents) to project West Coast sardine larvae distribution and habitat to improve the NMFS coastal pelagic sardine stock assessment required by the PFMC. A similar web-based effort has been developed by Bill Peterson (NOAA/NWFSC) that successfully forecasts salmon returns. See http://www.nwfsc.noaa.gov and click on "Ocean Index Tools."

The 2009 plans for PaCOOS include continuing coordination on proposal development with NOAA RAs emphasizing data management, ecological forecasting and assessment, and increasing ocean observing data when opportunities arise. In addition, an ecosystem status report is under development for the coastal pelagic species Stock Assessment and Fisheries Evaluation document.

Other Surveys Conducted in the California Current

Lines 60 and 67 Monterey Bay Aquarium Research Institute (MBARI), National Park Service (NPS), and University of California, Santa Cruz (UCSC) scientists continue to occupy Line 67 off Monterey and Line 60 off San Francisco with NOAA funding. A consistent suite of samples has been collected quarterly along Line 67 since 1997, and nearshore since 1989. In recent years, this shipboard work has been augmented by mooring, AUV and glider programs. The focus has been on: (1) seasonal/interannual/decadal temporal variations; and (2) Monterey Bay/upwelling system/California Current spatial variations. The data document California Current and Upwelling System dynamics over several ENSO cycles as well as a decadal to multi-decadal shift.

In 2008, MBARI and UCSC personnel collected nutrient, phytoplankton, and zooplankton samples during winter and spring cruises aboard RV *David Starr Jordan* (0801 and 0804). MBARI, NPS, and UCSC personnel conducted summer and fall cruises aboard the University-National Oceanographic Laboratory System RV *Point Sur* (S308 and S408). These data have been processed and quality-controlled, and are available both in the MBARI Biological Oceanography database and online. With the continued La Niña-like conditions of 2007, 2008 experienced unusually strong upwelling-favorable winds and in consequence, nearshore (≤30 nmi) surface waters were cold and salty and high in macronutrients and phytoplankton production and biomass. The effects of these conditions on fish, birds, and mammals have in some cases been surprising (seabird starvation, etc.). As analysis and publication proceed, the 2008 work will enable data-based exploration of: (1) the forecast shift from La Niña to El Niño later this year; (2) the putative decadal shift to cool conditions after 1998; and (3) secular climate change.

Trinidad Head Line

NOAA recently established an ocean observing effort (PaCOOS) in cooperation with Humboldt State University where data are collected at roughly monthly intervals along the Trinidad Head Line, which consists of six stations along a transect extending approximately 27 nm due west from Trinidad Head. Data reported here are based on temperature, salinity, and chlorophyll-*a* profiles from CTD casts to a maximum depth of 150 m at each station. Time series of these data have now reached a state where limited analysis of variability in the coastal ocean off northern California over time is possible (calculation of anomalies from a climatological mean is not currently viable) as well as comparisons to observations elsewhere along the coast.

All cruises were conducted aboard Humboldt State University's RV *Coral Sea* except for the March 2008 cruise which was conducted aboard the NOAA RV *Miller Freeman*. All sampling since November 2007, with the exception of cruises in March 2008 and 12 April 2009, has been conducted at night. Only three stations (TH02, TH03, and TH04) were sampled on 12 April 2009. The March 2008 cruise stands out with respect to the conditions just prior to and during sampling (25–50 knot southerly winds) that would have precluded operations aboard the *Coral Sea*.

The time series of observations along the Trinidad Head Line exhibits clear seasonal patterns, including the consequences of upwelling during spring and summer and warming and freshening of nearshore waters during the winter. Lenses of relatively fresh water, presumably associated with riverine plumes, are commonly encountered near the coast during mid-winter cruises, which underscores the role of freshwater input to nearshore hydrography during winter off northern California.

Spring 2008 was marked by relatively cold, salty water at depth on the shelf—the coldest and saltiest yet observed over the limited course of the time series—coupled with a broad cross-shelf extent of cool conditions in the upper water column. Cross-shelf patterns must be interpreted with some caution because offshore stations frequently encounter hydrographic structure extending southward from the coast between Cape Blanco, Oregon, and Point St. George, California, during periods of active upwelling.

Temporal and spatial patterns of chlorophyll-*a* concentrations reflect expected responses of the ecosystem to enrichment via upwelling. Not only were observed chlorophyll-*a* concentrations generally higher in 2008 than in 2007, areas of elevated chlorophyll-*a* concentration developed earlier and exhibited greater cross-shelf extent in 2008.

Shark Surveys The SWFSC's shark research group is responsible for collecting data to support the management of blue (*Prionace glauca*), shortfin mako (*Isurus oxyrinchus*) and common thresher sharks (*Alopias vulpinus*), all of which are common in the Southern California Bight and taken in regional fisheries, primarily as juveniles. Common thresher and mako sharks have the greatest commercial value and are also targeted by sport fishers. Although the blue shark has little market importance in the United States, it is a leading bycatch species in a number of U.S. fisheries and is targeted in Mexico. One of the primary methods used by NOAA Fisheries to collect data on the three species is fisheries-independent surveys. These surveys provide catch data that allow us to track trends in abundance. Use of fisheries data alone for estimating population status is complicated by changes in regulations, fishing methods, and areas over time. The surveys also provide the opportunity to deploy conventional and electronic tags, obtain biological samples and conduct studies on age and growth.

In June and July of 2008, the SWFSC conducted its fifteenth juvenile shark survey since 1994. Working aboard the FV *Ventura II*, a total of 6007 hooks at 29 sampling stations in seven main areas in the Southern California Bight were fished. Survey catch totaled 40 makos, 233 blue sharks, one common thresher, five pelagic rays (*Pteroplatytrygon violacea*) and one bat ray (*Myliobatis californica*). Nearly all of the sharks caught were injected with OTC for age and growth studies, tagged with conventional tags, and released. In addition, satellite tags were deployed on four blue sharks and nine shortfin makos. The cruise was conducted in two legs with 85% of the shortfin mako sharks caught during the second leg when higher water temperatures were encountered. The overall survey catch rate was 0.184 per 100 hook-hours for shortfin mako and 1.090 per 100 hook-hours for blue sharks. The nominal CPUE for blue sharks was somewhat higher than in 2007; however, there is a declining trend in nominal CPUE for both species over the time series of the survey.

In September of 2008, the SWFSC team worked with the F/V *Outer Banks* to sample common thresher sharks in the California Bight from Point Conception to the Mexican border. Forty-eight longline sets were made in relatively shallow near-shore waters. Over the 18-day cruise, catch totaled 300 common thresher sharks, two spiny dogfish (*Squalus acanthias*), 28 soupfin sharks (*Galeorhinus galeus*), two leopard sharks (*Triakis semifasciata*), and five brown smoothhound (*Mustelus henlei*). Nearly all of the common thresher sharks were injected with OTC for age and growth studies, tagged with conventional tags, and released. In addition, pop-off satellite tags were deployed on three common thresher sharks.

LUTH cruise Since 2006, NMFS has been studying swordfish in the Southern California Bight to examine migratory patterns, foraging ecology, and local stock structure. In 2008, researchers in the Fisheries Resources Division (FRD) teamed up with the Protected Resources Division (PRD) and the Southwest Region to launch a new initiative, Swordfish and Leatherback Utilization of Temperate Habitat (SLUTH). The overarching objective of SLUTH is to integrate studies of swordfish and leatherback sea turtles to inform management and conservation efforts. The endangered leatherback is taken incidentally in swordfish fisheries, and concerns about leatherback populations are currently shaping the management of swordfish along the U.S. West Coast.

A research goal of SLUTH is to characterize and quantify the habitat overlap of swordfish and leatherback sea turtles in vertical and geographic space. To this end, FRD and PRD staff collaborated to conduct a pilot project in conjunction with the PRD Leatherback Use of Temperate Habitat (LUTH) survey. The survey was conducted off central California aboard the NOAA RV *David Starr Jordan* in August and September 2008. The objectives of this first cruise focused on the feasibility of using one platform to conduct research on both species. If possible, this would allow the same temporal and spatial data collection and strengthen conclusions about habitat overlap. During the cruise, rather than sample along a grid pattern, sampling was dynamic and executed to capture the characteristics of oceanographic features thought to be important for defining leatherback or swordfish habitat. Sampling methods included using CTDs, net tows, acoustics, and aerial surveys. Fishing via longline was used to determine patterns of occurrence of swordfish. During the cruise, four longline sets were conducted in three different areas. Four swordfish were captured on two sets, both of which occurred on the warm side of a frontal system, and two animals were taken for sampling. In addition to the swordfish, 65 blue sharks and three mako sharks were caught and released. Efforts provided important insight into swordfish distributions and an important proof of concept for this type of multidisciplinary research approach.

West Coast Midwater Trawl Survey The ninth annual West Coast midwater trawl survey was conducted during the peak of the upwelling season from 20 May–25 June 2009. This coast-wide survey represents a major geographical expansion of the traditional SWFSC Fisheries Ecology Division's pelagic juvenile rockfish survey, which was fielded in the central California region between Carmel and Bodega Bay. The survey now spans the entire U.S. West Coast and in 2009 extended from San Diego, California (lat. 32°42'N), to Cape Alava, Washington (lat. 48°06'N). In previous years the expanded survey was conducted using two vessels, usually the NOAA RV *David Starr Jordan* and the FV *Excalibur*. The latter vessel hails from Newport, Oregon, and operates under a cooperative research contract between the NWFSC and the Pacific Whiting Conservation Cooperative. This year, however, because the *David Starr Jordan* was tied up due to budgetary constraints, the NOAA RV *Miller Freeman* was deployed instead. The use of a new ship in this fishery-independent survey required inter-vessel calibration, which was achieved by 20 joint, paired trawls of the two ships that occurred at the same time and place over a five-day period between Monterey Bay and Fort Ross. Both vessels use identical trawl gear, i.e., a 12 m × 12 m modified Cobb midwater trawl equipped with a 3/8" cod-end liner, with a standard trawl consisting of a 15-min tow at a headrope depth of 30 m.

Sampling is focused on young-of-the-year (YOY) groundfish, including especially rockfishes (*Sebastes* spp.), Pacific whiting, lingcod (*Ophiodon elongatus*), rex sole (*Glyptocephalus zachirus*), and sanddabs (*Citharichthys* spp.). In addition, a wide variety of other epipelagic micronekton are captured and enumerated, including krill (*Euphausia pacifica* and *Thysanoessa spinifera*), market squid (*Loligo opalescens*), lanternfishes (*Diaphus theta*, *Tarletonbeania crenularis*, *Stenobrachius leucopsarus*, *Lampanyctus* spp.), northern anchovy, and Pacific sardine.

The catch rate of YOY rockfish continued to increase this year, after hitting a record low of 0.61 rockfish/trawl in 2005. Since that time, catch rates have approximately doubled each year, with a catch rate of 19.60 rockfish/trawl recorded this year. Catches of other YOY groundfish were also up, as were catches of krill.

The CalCOFI Committee:
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REVIEW OF SELECTED CALIFORNIA FISHERIES FOR 2008: COASTAL PELAGIC FINFISH, MARKET SQUID, OCEAN SALMON, GROUNDFISH, CALIFORNIA SPINY LOBSTER, SPOT PRAWN, WHITE SEABASS, KELP BASS, THRESHER SHARK, SKATES AND RAYS, KELLET'S WHELK, AND SEA CUCUMBER

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SUMMARY

In 2008, commercial fisheries landed an estimated 141,377 metric tons (t) of fishes and invertebrates from California ocean waters (fig. 1). This represents a decrease of nearly 18% from the 172,125 t landed in 2007, and a 44% decline from the peak landings of 252,568 t observed in 2000. The preliminary ex-vessel economic value of commercial landings in 2008 was nearly $112 million, a decrease of 7% from the $120 million in 2007.

Pacific sardine (*Sardinops sagax*) remained the largest volume fishery in the state at nearly 58,000 t even though landings dropped by nearly a third from 2007. Although the fishery took nearly all of the allocation, the decline in landings was due to a more restrictive harvest guideline (HG) based on declining stock abundance. Market squid (*Loligo apalescens*) was second in landings at over 36,000 t. Other species in the top-five volume fisheries included northern anchovy (*Engraulis mordax*) at 14,200 t, Pacific whiting (*Merluccius productus*) at 4,900 t, and red sea urchin (*Strongylocentrotus franciscanus*) at 4,700 t. Market squid was the highest valued fishery at $25.3 million followed by Dungeness crab (*Cancer magister*) at $22.4 million. Other species in the top-five valued fisheries include California spiny lobster (*Panulirus interruptus*) at nearly $7.9 million, Pacific sardine at $7.6 million and red sea urchin at $6.5 million.

Noticeably absent from the 2008 high value fisheries was Pacific Chinook salmon (*Oncorhynchus tshawytscha*). The Pacific Fishery Management Council (Council), the National Marine Fisheries Service (NMFS), and the California Fish and Game Commission (Commission) closed the recreational and commercial ocean salmon fishing seasons in April 2008 because Sacramento River fall Chinook (SRFC) were projected to not meet their Salmon Fishery Management Plan (FMP) conservation objective. In 2008, no commercial landings occurred compared to total commercial landings of 114,141 Chinook (686 t) in 2007 valued at $7.8 million. In the 2008 recreational fishery, six fish were landed during February and March in Fort Bragg (prior to an emergency closure enacted on 1 April 2008) compared to 47,704 salmon landed in California during 2007.

California's commercial groundfish harvest for 2008 (13,000 t) increased 25% over landings in 2007 (10,500 t). Pacific whiting, Dover sole (*Microstomus pacificus*), and sablefish (*Anoplopoma fimbria*) continued to be the top species landed. The ex-vessel value of groundfish landings for 2008 was $19.7 million, 12% higher than in 2007, but still 12% lower than the peak value in 1998. A review of the status of yelloweye rockfish (*Sebastes ruberrimus*) is also provided in this report.

In 2008, commercial landings of California spiny lobster were nearly 335 t and valued at $7.9 million. A recreational report card for lobster was first introduced for the 2008–09 recreational season with nearly 25,000 cards sold at the beginning of the season. Recent investigations by the California Department of Fish and Game (Department) indicate that recreational effort has switched primarily from divers to hoop netting, and that the new rigid hoop nets are more effective at catching lobsters.

Commercial 2008 spot prawn landings were 130 t, a 9% increase from 2007. Almost all spot prawns are sold live with one of the highest ex-vessel prices, ranging from $22/kg to $31/kg, resulting in a fishery valued at $3.2 million.

Commercial landings of white seabass (*Atractoscion nobilis*) in 2008 (291 t) increased 41% over 2007, while recreational landings decreased by 11% from 57 t to 51 t in 2008. The combined commercial and recreational catch for 2008 was 342 mt. Disease issues within the hatchery and growout facilities in 2008 reduced hatchery-raised white seabass releases by 71% from 2007.

Nearly 200,000 kelp bass (*Paralabrax clathratus*), one of the most popular species caught by recreational anglers in southern California, were landed in 2008. This is a 15% decline from 2007 and a 19% decline from the ten-year average from 1999 to 2008.

Skates and rays are not usually targeted in commercial fisheries, but have been primarily taken as incidental catch by trawlers in California. In 2008, commercial landings for skates totaled 177 t, the highest landings since 2001 and were valued at nearly $97,000. The most common species landed include big (*Raja binoculata*), California (*Raja inornata*), and longnose (*Raja rhina*) skates.

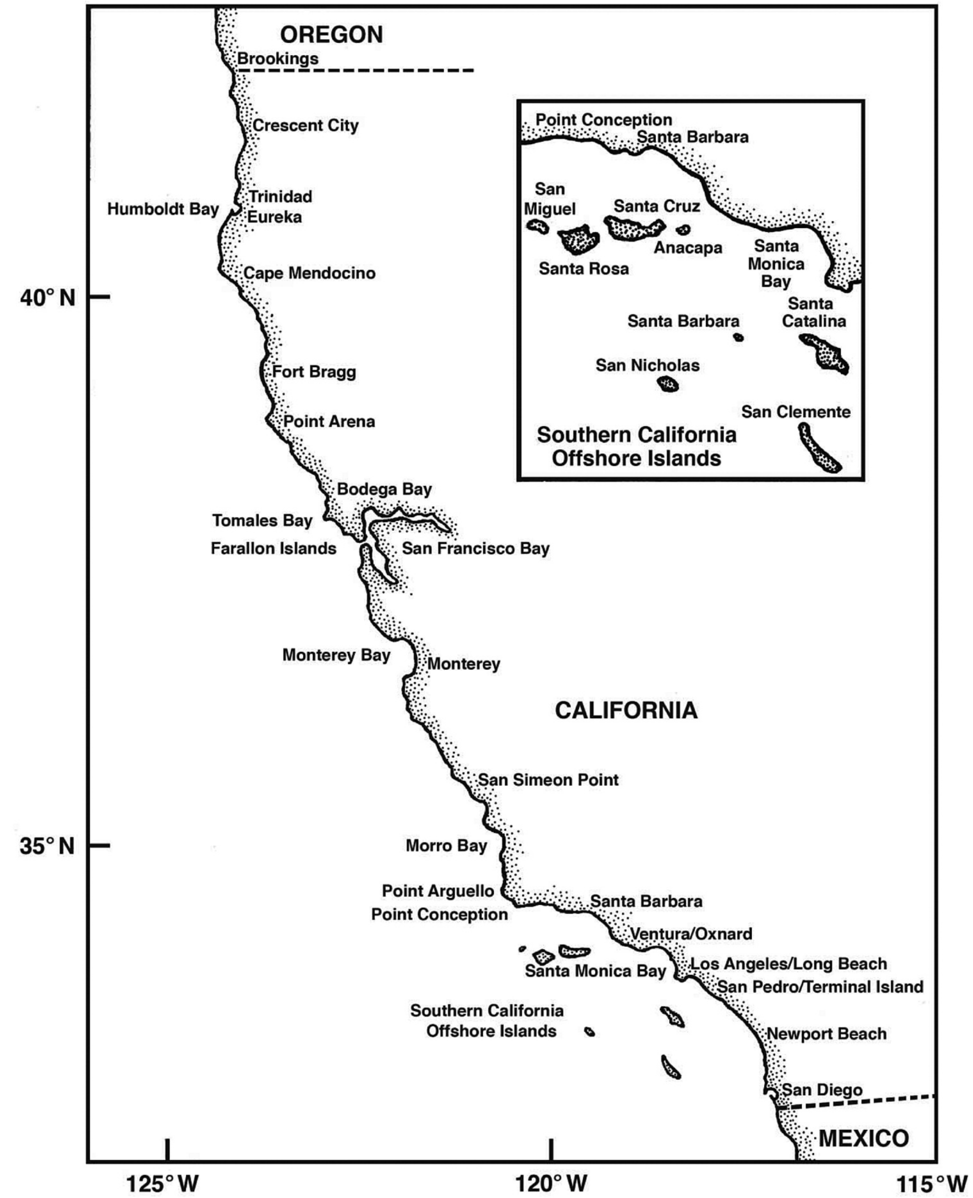

Figure 1. California ports and fishing areas.

For rays, landings totaled 10.4 t and were valued at nearly $12,000. Bat rays and shovelnose guitarfish accounted for over 70% of ray species landed.

Concern over a rapidly expanding recreational fishery for thresher shark (*Alopias* spp.) led to an evaluation of the current thresher shark management strategies by NMFS and the Department. Although no actions were taken by the Council at the time, several recommendations including a new stock assessment, investigations to better estimate the number and condition of released fish and to determine if gear modifications can increase survival were initiated.

Two interesting invertebrate fisheries are also reviewed. An update of the Kellet's whelk (*Kelletia kelletii*) fishery, first described in the 2006 CalCOFI report, indicates that in 2008, landings (73 t) decreased by 6% from 2007 and 16% from the peak landings in 2006. In contrast, 2008 sea cucumber (*Parastichopus* spp.) landings (370 t) increased by two thirds over 2007 landings and increased in value by over a million dollars.

In 2008, the Commission undertook 10 rule-making actions that addressed marine and anadromous species. The Commission adopted changes to salmon, groundfish, sea urchin, halibut, prawn, shrimp, herring and Dungeness crab regulations and revised commercial permit renewals. The Commission also finalized plans for a series of 24 marine protected areas (153 square miles) in the north-central coast region, defined as State waters

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	2,709	68,646
1999	56,747	5,179	9,527	963	2,207	90,322	164,945
2000	53,586	11,504	21,222	1,135	3,736	117,961	209,144
2001	51,811	19,187	6,924	3,615	2,715	85,828	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
2005	34,599	11,178	3,243	199	219	55,407	104,845
2006	46,672	12,815	5,904	1,169	37	49,248	115,845
2007	80,950	10,390	5,018	632	597	49,438	147,025
2008	57,803	14,285	3,535	274	757	36,596	113,250

Data Source: Commercial Fisheries Information System (CFIS)

between Point Arena (Mendocino County) and Pigeon Point (San Mateo County) under the Marine Life Protection Act. In addition, the Commission removed the California Brown Pelican (*Pelecanus occidentalis californicus*) from the list of rare and endangered species pursuant to the California Endangered Species Act.

Coastal Pelagic Finfish

Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), northern anchovy (*Engraulis mordax*), and Pacific herring (*Clupea pallasi*) are part of a finfish complex known as coastal pelagic species (CPS). These species, with the exception of Pacific herring, are jointly managed by the Council and NMFS. In 2008, total commercial landings for these four species equaled 75,897 t (tab. 1), and were worth nearly $9.9 million in ex-vessel value. Compared to landings in 2007, this represents a 29% and 4% decrease in quantity and ex-vessel value, respectively. Once again Pacific sardine ranks as the largest fishery among these four species, contributing 51% of the combined quantity and 77% of the combined ex-vessel value.

TABLE 2
Landings (metric tons) of Pacific sardine (*Sardinops sagax*) and Pacific mackerel (*Scomber japonicus*) at California port areas in 2008.

	Pacific Sardine		Pacific Mackerel	
Area	Landings	% Total	Landings	% Total
Eureka	0	0	0	0
San Francisco	500	1	0	0
Monterey	26,212	45	206	6
Morro Bay	0	0	0	0
Santa Barbara	142	0	136	4
Los Angeles	30,949	54	3,187	90
San Diego	0	0	0	0
Total	57,803	100	3,529	100

Data Source: CFIS

Pacific Sardine. In 2008, the total tonnage of Pacific sardine landed (57,803 t) was 29% lower than in 2007 (80,950 t) due in large part to an HG that was 48% lower than in 2007. California landings of Pacific sardine generated an ex-vessel value of approximately $7.6 million. Commercial landings of sardine averaged 51,910 t over the ten-year period from 1999–2008 (fig. 2). Nearly all (99%) of California's 2008 sardine catch was landed in Los Angeles (54%, 30,949 t) and Monterey (45%, 26,212 t) port areas (tab. 2). In 2008, California exports of sardine product decreased by 23% over 2007 exports (66,896 t).

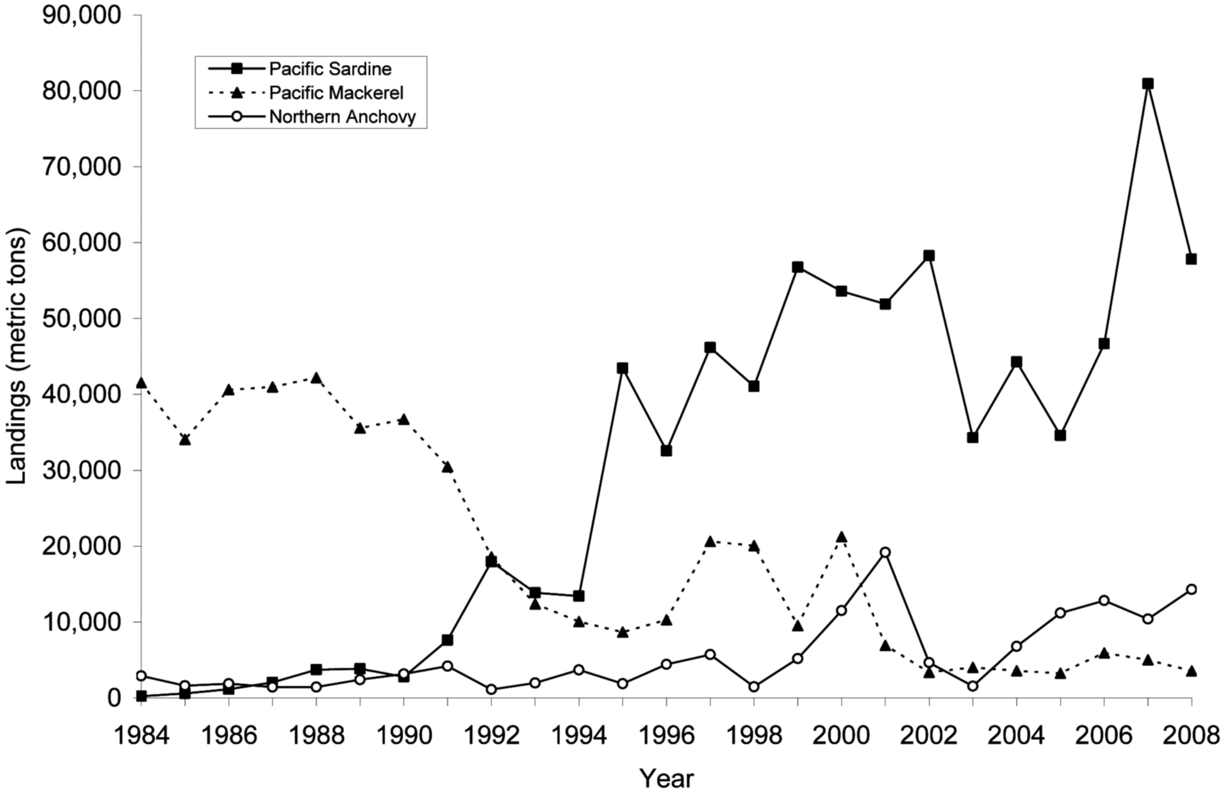

Figure 2. California commercial landings of Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), and northern anchovy (*Engraulis mordax*), 1984–2008.

A total of 51,844 t of sardine product was delivered to 30 countries. The majority (72%) of this product was exported to Australia (16,457 t), Japan (11,259 t), and Thailand (9,409 t). These three countries represent 66% of the total export value of approximately $37 million.

The Pacific sardine fishery ranges from British Columbia, Canada, southward to Baja California, Mexico (BCM). Since the 1970s the majority of landings have occurred in southern California and northern Baja California. However, since the expansion of the sardine fishery in 1999, landings have steadily increased in the Pacific Northwest. The combined landings of Pacific sardine for California, Oregon, and Washington totaled 87,183 t in 2008, down 30% from the 127,597 t landed in 2007. The Pacific sardine HG for each calendar year is determined from the previous year's stock biomass estimate (of ≥1-year-old fish on 1 July) in U.S. and Mexican waters. The HG for the 2008 season was 89,093 t based on a biomass estimate of 832,706 t. This was 48% lower than the HG for 2007. The Pacific sardine HG was apportioned coast-wide through the year with 35% allocated from 1 January through 30 June, 40% allocated plus any portion not harvested in the previous allocation from 1 July through 14 September, and the last 25%, plus any portion not harvested from the first two allocations, released on 15 September.

In 2008, U.S. west coast fisheries harvested a greater proportion (98%) of the HG compared to the previous year (84%). The 1st allocation (1 Jan–30 June) lasted 150 days. This was markedly longer than the 2nd (1 July–14 Sept) and 3rd (15 Sept–31 Dec) allocations, which lasted 40 and nine days, respectively. Increased fishing efforts, such as multiple landings per day, were observed during all allocation periods. During the 2nd and 3rd allocations, fishing effort continued during weekends, a period normally not fished. The 2008 fishery behavior was characteristic of a "derby" style fishery, resulting in a temporally shortened directed fishery. The directed Pacific sardine fishery was officially closed by NMFS on 23 September 2008.

The steady increase of sardines landed in Oregon since 1999 may have leveled off or slowed in the last three years (fig. 3). Oregon landings of sardine totaled 22,949 t in 2008, a considerable decrease from 2007 (42,144 t). In 2008, Oregon exported 4,050 t of sardine product worth a little over $3.8 million.

Washington landings of Pacific sardine decreased to 6,435 t in 2008 since a peak in 2000 (15,832 t, fig. 3). This is an increase from 2007 (4,665 t). Washington exported more sardine (19,201 t) than they landed (6,435 t), possibly product that was landed in Oregon or California or landed in 2007.

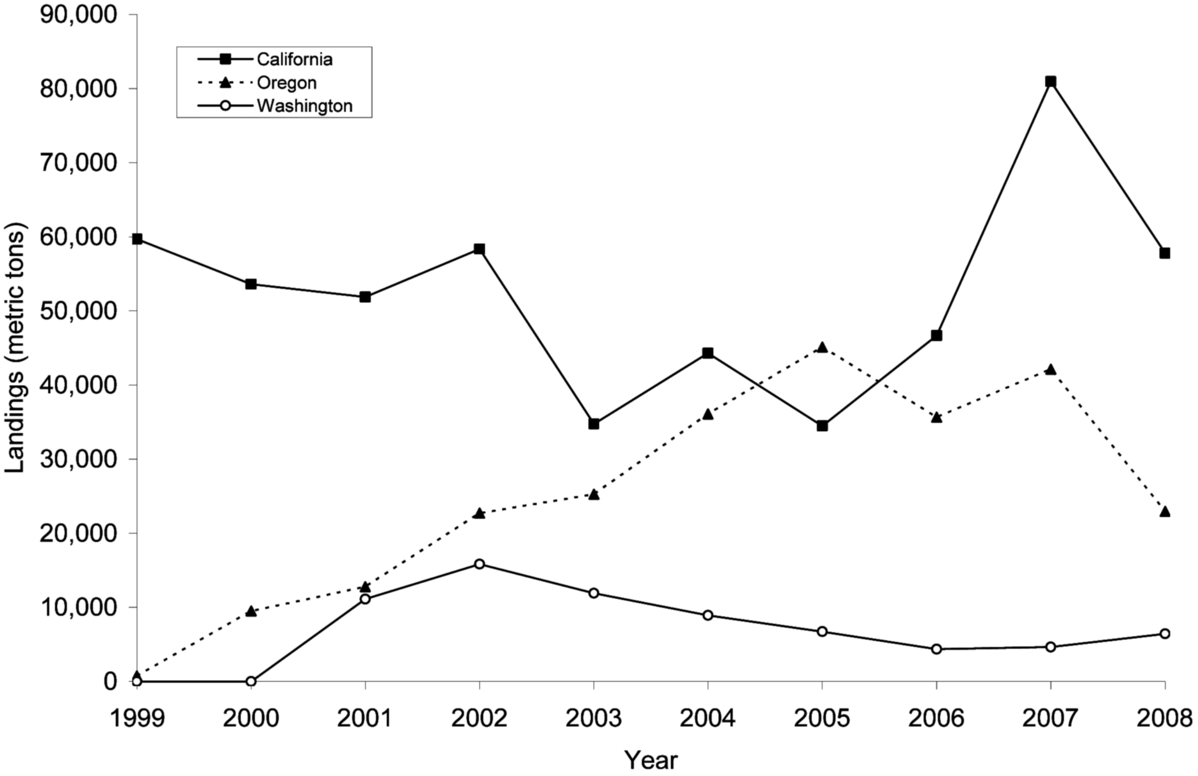

Figure 3. Commercial landings of Pacific sardine (*Sardinops sagax*) in California, Oregon, and Washington, 1999–2008.

In November 2008, the Council adopted an HG of 66,932 t for the 2009 Pacific sardine fishery based on a biomass estimate of 662,886 t and the harvest control rule in the CPS FMP. This HG is a 25% reduction from the 2008 HG. It also incorporated a new-for-2009 2,400 t set-aside allocated for dedicated Pacific sardine research activities during the 2nd allocation period.

The 2008 recreational Pacific sardine catch as sampled from the California Recreational Fisheries Survey (CRFS) was 29 t (595,000 fish), a 142% (185%, by number of fish) increase from 2007. The majority of the fish landed were from man-made structures, such as piers (97% by number and 100% by weight).

Pacific Mackerel. Pacific mackerel landings in California continue to be relatively low with 3,535 t in 2008 (tab. 1) following a seven-year trend (fig. 2). A majority of this catch was landed in southern California port areas (tab. 2). The total ex-vessel value generated for Pacific mackerel in 2008 was $686,589. Industry exported 1,876 t of mackerel product, valued at nearly $1.6 million, to 22 countries. China (405 t), Nauru (240 t), and Indonesia (227 t) received over 46% of this product.

Oregon reported 58 t of Pacific mackerel landed there in 2008 for a total ex-vessel value of $7,810. This is considerably down from the 2007 catch of 702 t. No landings of mackerel have been reported in Washington since 2005. Washington landings of Pacific mackerel are typically low, with an annual average of 72 t (unspecified mackerel) since 1999.

Similar to sardines, the majority of Pacific mackerel landings occur in southern California and Ensenada, BCM. In the U.S., the fishing season for Pacific mackerel is 1 July to 30 June the following year. At the start of the 2008–09 season NMFS estimated the biomass at 264,732 t and the Council set the HG at 40,000 t, with an 11,772 t set-aside for incidental landings in other fisheries. These values are lower than the prior season (biomass: 359,290 t; HG: 40,000 t). Landings above the HG would be constrained by an incidental catch rate of 45% by weight when landed with other CPS.

The 2008 recreational Pacific mackerel catch as sampled from CRFS was 291 t (1,904,000 fish), a 22% (45%, by number of fish) increase from 2007. Commercial passenger fishing vessels (CPFVs) reported 49,150 fish landed with <1% landed in Mexico.

Jack Mackerel. In 2008, jack mackerel landings represented less than 1% of the total catch of CPS in California with 274 t landed. This is less than half of the total 2007 catch (632 t) and generated $57,354 in ex-vessel revenue. Landings in Oregon continue to be low with 46 t landed in 2008 for an ex-vessel value of $415. Washington reported no landings of jack mackerel during 2008.

The 2008 recreational jack mackerel catch as sampled

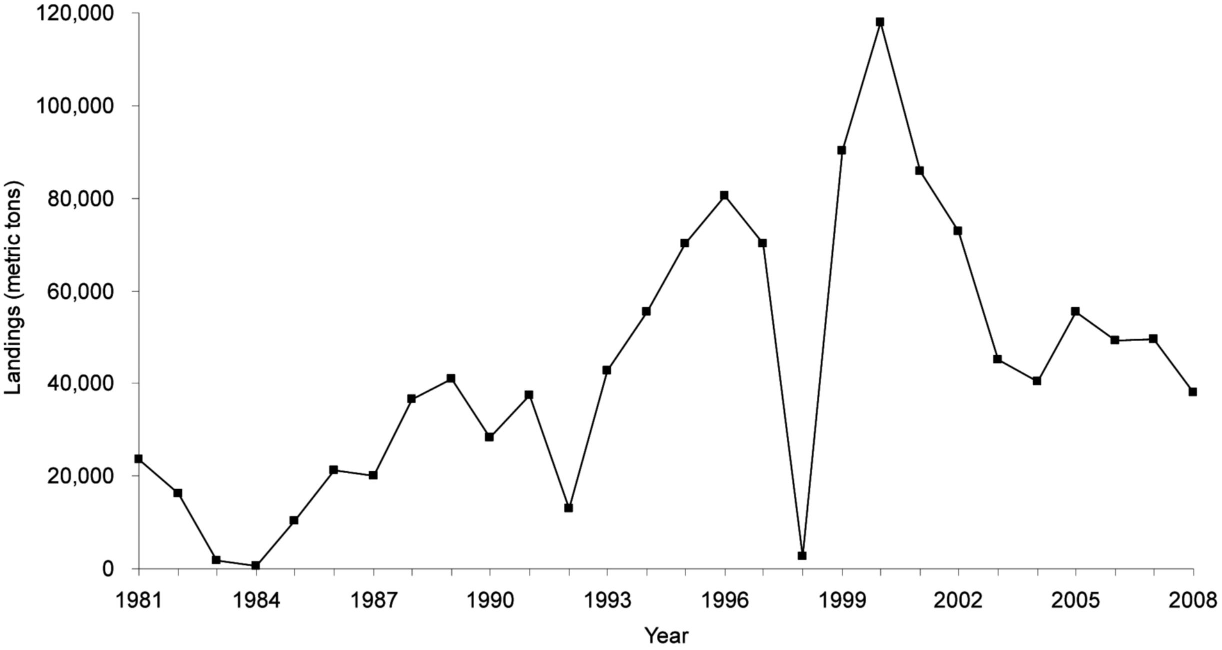

Figure 4. California commercial market squid (*Loligo opalescens*) landings, 1981–2008.

from CRFS was 5 t (86,000 fish), a 67% (161%, by number of fish) increase from 2007. CPFV vessels reported 408 fish landed.

Northern Anchovy. Landings of northern anchovy in California have been reported since 1916. Historically, anchovy was reduced to oil or fish meal and the fishery was modest compared to Pacific sardine and Pacific mackerel. However, periods of low sardine abundance saw increased anchovy landings. Peak landings were seen in the early-to-mid 1970s with total annual harvest exceeding 100,000 t at times. Presently, landings of northern anchovy are relatively modest, averaging about 9,800 t per year over the last 10 years (fig. 2). The vast majority of northern anchovy are landed in California, with occasional landings in Oregon and Washington. Anchovy are currently used for human consumption, animal food, and live bait.

California landings of northern anchovy in 2008 amounted to 14,285 t (tab. 1) with an ex-vessel value of nearly $1.6 million. This is a 37% increase from 2007 landings (10,390 t) and ranked as the second most valuable CPS finfish after Pacific sardine. Exports of northern anchovy product from California totaled 564 t for an export value of $338,303. While six countries received anchovy product from California, South Korea and Australia received the majority at 50% and 48%, respectively.

For 2008, Oregon reported landings totaling 260 t with an ex-vessel value of $56,674. Oregon exports of anchovy totaled 23 t to China with a value of $80,505. Washington reported 109 t valued at $35,280 ex-vessel value for 2008. Approximately 42 t was exported to Thailand with a value of $103,166. The 2008 California recreational catch for northern anchovy as sampled by CRFS totaled 3 t (194,000 fish).

Pacific Bonito. From 1999–2008, annual Pacific bonito (*Sarda chiliensis lineolata*) landings averaged 405 t, a small percentage of the total CPS quantity landed in California. In 2008, landings increased 262% from last year's low of 222 t to 803 t. The landings generated an ex-vessel value of $644,528. No landings of Pacific bonito were reported from Oregon or Washington in 2008.

The California recreational catches for Pacific bonito in 2008 were 146 t (76,000 fish), a 128% increase from 2007, although there was a 26% decrease in the number of fish. This disparity is the result of an increase in the average size of bonito landed from 384 mm (15.1 in.) in 2007 to 449 mm (17.7 in.) in 2008, and an increase in the average weight from 0.9 kg (2.0 lb.) in 2007 to 1.5 kg (3.3 lb.) in 2008. CPFV vessels reported 101,604 fish landed with 10.57% landed in Mexico.

California Market Squid

Of all the marine commercial species landed in California during 2008, market squid, *Loligo* (*Doryteuthis*) opalescens, generated the most ex-vessel revenue and ranked second in volume. Landings in 2008 were just 77% of the 2007 landings, at 38,100 t compared to 49, 473 t (fig.4). The ex-vessel value also dropped from $29.1 million in 2007 to $26.5 million. However, the ex-vessel price per ton of market squid has increased in recent years. In 2008, the average ex-vessel price was $639/t,

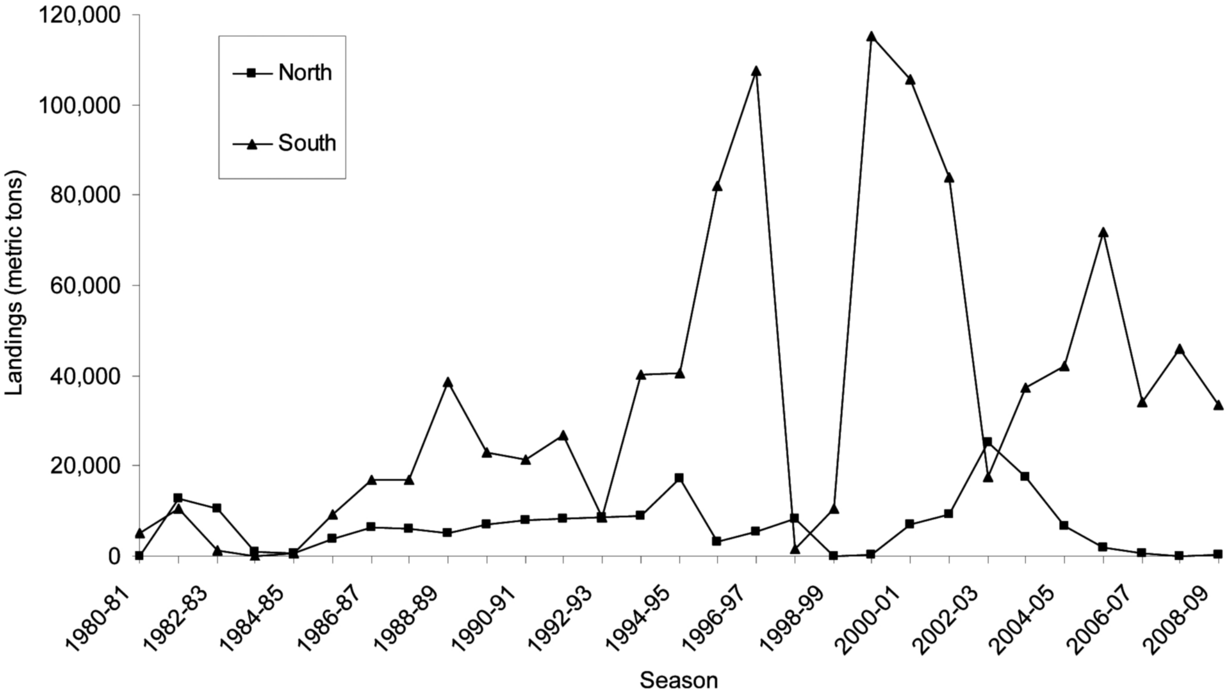

Figure 5. Comparison of market squid (*Loligo opalescens*) landings for northern and southern fisheries by fishing season (1 April–31 March), from 1980–81 to 2008–09 seasons.

up from $597/t in 2007 and $560/t in 2006. California fish businesses exported 25,371 t of market squid to 28 countries for a value of $35.8 million in 2008. The majority of those exports were to China (70%) with no other country contributing more than 5% of the market share.

The fishery can be separated into a northern and southern component based on the timing of when environmental conditions are optimal for squid spawning. The northern component is centered in and around Monterey Bay in the spring and summer, while the southern component is centered in the Southern California Bight usually in the fall and winter. Although the fishery has its historical origins in Monterey Bay, the fishery has been dominated by the southern component especially in the last few seasons, which have seen minimal landings in the northern component (fig. 5).

The fishery targets market squid during spawning events when they form dense schools usually over shallow sandy substrate. The fishery primarily uses purse and drum seine vessels with attracting lights to catch market squid, often working with a smaller vessel called a light boat, which also attracts squid using lights. A third type of vessel, a brail boat, uses attracting lights and scoops squid from the water using a dip net. A commercial live-bait fishery now exists for market squid; however, the amount of market squid harvested and the value of the fishery are largely unknown, as there are no permitting and reporting requirements. The live-bait fishery is likely a low-volume, high-value endeavor, as recreational anglers, primarily targeting white seabass, are willing to pay up to $85 for a "scoop" of live squid.

Commercial fishing for market squid is limited by fishery control rules set forth in the Market Squid FMP. Vessels are required to have a permit to possess or land over two short tons (1.8 t) of squid, except when fishing for use as live bait. The fishing permit is valid from 1 April to 31 March the following year. The number of permits issued per annum has declined from a high of 296 in 1998 to 211 in 2004. In 2005, a new permit structure was put into place and the number of permits issued has remained relatively constant at around 175. In 2008, there were 83 transferable market squid vessel, 59 light boat, 22 brail, 11 nontransferable market squid vessel, and three nontransferable light boat permits issued. Other fishery control rules include an annual catch limit of 107,048 t (118,000 short tons), weekend closures, lighting requirements, area closures for birds, and the use of an egg escapement model as a proxy for maximum sustainable yield (MSY).

Ocean Salmon

Ocean salmon fisheries in California primarily target Chinook salmon (*Oncorhynchus tshawytscha*). The retention of coho salmon (*O. kisutch*) has been prohibited in the commercial and recreational fisheries since 1993 and 1996, respectively. Pink salmon (*O. gorbuscha*) are taken occasionally in the fisheries, usually in odd years. Each season, the Council and the Commission regulate California's ocean salmon fisheries to meet the conservation objectives for Klamath River fall Chinook and SRFC stocks as described in the Salmon FMP. In addition, the fisheries must meet the NMFS Endangered Species Act (ESA) consultation standards for listed stocks, including Sacramento River winter Chinook (endangered), Central Valley spring Chinook (threatened), California coastal Chinook (threatened), Central California coast coho (endangered), and southern Oregon/northern California coho stocks (threatened).

In 2008, California salmon fisheries were closed due to a significant decline in the abundance of SRFC. This stock generally contributes 80%–90% of California's ocean landings. In the fall of 2008, only 66,264 SRFC adults returned to spawn in the Sacramento River basin, which was the lowest escapement on record and is well below the FMP's conservation goal of 122,000–180,000 adult spawners. In addition, only 4,061 SRFC jacks (age-2 fish) returned to spawn in 2008, the second lowest return on record. The number of returning jacks is used to estimate the following year's adult ocean abundance. Based on these data, the forecasted ocean abundance for 2009 was approximately 122,196 SRFC, without any additional ocean or river fishing. This would predict the third-lowest adult escapement of SRFC since 1992. In April 2009, the Council and Commission closed all commercial and severely limited recreational ocean salmon fishing in California during 2009, specifically to protect SRFC.

No commercial landings occurred in 2008 compared to estimated total commercial landings of 114,141 Chinook (686 t) in 2007. There were zero days open compared to 341 (days open in each of four management areas combined) in 2007.

The 2008 recreational fishery was open for 45 days in the Fort Bragg area prior to the 1 April closure, compared to a season total of 794 days (days open in each of four management areas combined) in 2007. In the abbreviated 2008 recreational fishery an estimated six Chinook were landed compared to 47,704 salmon in 2007. There were an estimated 391 angler days in 2008 compared to 105,889 angler days in 2007. No salmon were landed by CPFVs. Regulations permitted two salmon per day of any species except coho. Single point, single-shank barbless hooks were required north of Point Conception and anglers fishing with bait and by any means other than trolling were required to use circle hooks. The minimum size limit was 508 mm (20 in.) total length (TL).

In 2009, a limited recreational fishery was set for the Eureka and Crescent City major port areas from 29 August through 7 September 2009. The waters from the Oregon border to Horse Mountain, California will be open to ocean sport anglers. Regulations permit two salmon per day of any species except coho. Single point, single-shank barbless hooks are required north of Point Conception and anglers fishing with bait and by any means other than trolling are required to use circle hooks. The minimum size limit is 609 mm (24 in.) TL.

Groundfish

More than 90 species of bottom-dwelling marine finfish are included in the federally-managed groundfish species complex. The groundfish fishery includes all rockfishes, sablefish (*Anoplopoma fimbria*), thornyheads (*Sebastolobus alascanus* and *S. altivelis*), lingcod (*Ophiodon elongates*), Dover sole (*Microstomus pacificus*) and other flatfishes (not including halibut), Pacific whiting (*Merluccius productus*), and some sharks and skates.

Commercial Fishery. In 2008, 13,109 t of commercial groundfish were landed in California. This is a 25% increase from landings in 2007 (10,513 t, tab. 3), a 9% increase from 2006 landings (12,047 t), and a 44% decrease from 1998 landings (23,364 t). Pacific whiting (4,944 t), Dover sole (3,018 t), and sablefish (1,549 t) continued to be the top species landed by weight in 2008, identical to species dominating landings in 1998, 2006, and 2007. Dover sole, thornyheads, and sablefish (collectively referred to as the "DTS" complex) landings accounted for 73% (9,511 t) of all commercial groundfish landings. Overall in 2008, the species groups caught most frequently were roundfishes (e.g., sablefish, lingcod, cabezon (*Scorpaenichthys marmoratus*), greenlings (*Hexagrammos* spp.), Pacific whiting (*Merluccius productus*), and Pacific cod (*Gadus macrocephalus*) (50%), followed by flatfishes (34%) and rockfishes (14%). Sharks and skates accounted for two percent of the total commercial groundfish landings. The most important rockfish species to the 2008 commercial groundfish fishery in terms of total landings by weight (101 t) was chilipepper rockfish (*Sebastes goodie*); black rockfish (*Sebastes melanops*) was the most important in terms of ex-vessel value ($438,000). Overfished rockfish species accounted for less than one percent (68 t) of the landings in 2008, although 21% more were landed than in 2007 (56 t); the predominant species was widow rockfish (*Sebastes entomelas*) in both years.

The 2008 ex-vessel value for commercial groundfish was approximately $19.7 million, a 12% increase from 2007 ($17.6 million), and a 12% decrease from the peak in 1998 ($22.4 million). Among species with landings greater than one metric ton per year, grass rockfish (*Sebastes rastrelliger*) was the most valuable species landed in 2008 with an average price of $11.46/kg, followed by China rockfish (*Sebastes nebulosus*) at $8.46/kg, and gopher rockfish (*Sebastes camatus*) $8.16/kg. The high market value of these species is due to their live condi-

TABLE 3
California commercial groundfish landings (in metric tons) and ex-vessel value in 2008 with comparisons to 2007. The top five species by weight for flatfish and rockfish species groups are represented in the table.

	2008		2007			
	Harvest (t)	Value ($)	Harvest (t)	Value ($)	% change from 2007 (t)	% change from 2007 ($)
Flatfishes						
Arrowtooth flounder	44.5	$9,896	60	$13,556	–26%	–27%
Dover sole	3,018	$2,576,384	2,767	$2,378,010	9%	8%
English sole	139	$109,650	181	$143,256	–23%	–23%
Petrale sole	923	$2,187,129	916	$2,122,955	1%	3%
Rex sole	142	$112,274	172	$132,952	–17%	–16%
Sanddabs	126	$132,131	162	$170,337	–22%	–22%
Other flatfish	28	$42,767	46	$7,1967	–39%	–40%
Total Flatfishes	4,420	$5,170,231	4,305	$5,033,033	3%	3%
Rockfishes						
Chilipepper rockfish	101	$192,346	57	$103,278	76%	86%
Black rockfish	99	$437,968	81	$357,522	22%	23%
Bank rockfish	71	$158,210	26	$63,214	175%	150%
Splitnose rockfish	71	$61,234	80	$61,663	–12%	–1%
Blackgill rockfish	40	$148,029	25	$87,698	59%	69%
Gopher rockfish	24	$394,018	20	$312,944	21%	26%
Other rockfish	191	$1,425,288	238	$1,538,591	–20%	–7%
Overfished species						
Bocaccio	6	$18,260	7	$20,965	17%	15%
Canary rockfish	1	$1,537	0.8	$1,395	–20%	–9%
Cowcod	No Data	0.1	$130			
Darkblotched rockfish	30	$39,606	41	$53,704	–27%	–26%
Pacific ocean Perch	0.2	$223	0.03	$27	567%	726%
Widow rockfish	31	$100,461	8.3	$19,899	273%	405%
Yelloweye rockfish	0.02	$34	0.2	$801	–90%	–96%
Total Rockfishes	665	$2,977,345	587	$2,622,147	14%	14%
Roundfishes						
Cabezon	23	$310,362	25	$326,941	–8%	–5%
Kelp greenling	1.3	$20,046	1.5	$20,760	–13%	–3%
Lingcod	69	$236,514	80	$258,822	–14%	–9%
Pacific whiting	4,944	$1,646,925	2,968	$1,956,261	67%	–16%
Sablefish	1,549	$6,230,990	1,448	$4,882,907	7%	28%
Total Roundfishes	6,587	$8,444,837	4,523	$7,445,691	46%	13%
Scorpionfish, California	3.6	$25,722	3.6	$25,657	0%	0%
Sharks & Skates	232	$155,864	147	$109,405	58%	42%
Thornyheads	1,110	$2,866,271	844	$2,322,391	32%	23%
Other Groundfish	92	$43,243	105	$41,394	–12%	4%
Total Groundfish	12,967	$19,571,239	10,339	$17,466,766	25%	12%

Data Source: CFIS

tion and limited availability. The majority of groundfish landed in 2008 were taken by trawl gear (89%). The remainder was caught with hook-and-line gear (9%) and trap gear (2%). Net gear accounted for less than one percent of the total catch. Pacific whiting and Dover sole were the main contributors to trawl landings.

Recreational Fishery. The Recreational Fisheries Information Network (RecFIN) Program houses recreational data from California, Oregon, and Washington. The California data, available from 1980 to present, provide the best available information regarding recreational catch off California. RecFIN incorporates two recreational fishery sampling programs: the Marine Recreational Fisheries Statistical Survey (MRFSS), which sampled from 1980 to 2003, and CRFS, which was initiated by the Department in 2004. Due to changes in the sampling protocol and how the data are used to estimate landings, these two surveys are not comparable. Information from CRFS indicated that in 2008, California anglers targeting bottomfish participated in an estimated 798,000 trips. This was an 8% increase from 2007 (734,000 angler trips) and a 36% increase from 2006 (587,000 angler trips). Seventy-nine percent of the bottomfish effort occurred in southern California (south of Point Conception), particularly from CPFVs and man-made structures. Central California (Point Conception to Cape Mendocino) accounted for 17% of the bottomfish effort and northern California (Cape Mendocino to the California/Oregon border) accounted for four percent. An estimated 945 t of groundfish were taken by the recreational fishery in 2008 (tab. 4), a 27% decrease from 2007 (1,292 t) and a 41% decrease from 2006 (1606 t). The top five species accounting for approximately half (52%) of the groundfish catch by weight were

TABLE 4
California recreational groundfish landings (A+B1)* greater than 5 metric tons in 2008 with 2007 comparisons

	2007 Harvest (t)	2008 Harvest (t)	% Change from 2007
Black Rockfish	139	150	9%
Vermilion Rockfish	195	104	–47%
Lingcod	174	99	–43%
Blue Rockfish	148	83	–44%
CA Scorpionfish	68	60	–12%
Brown Rockfish	56	48	–14%
Copper Rockfish	67	48	–27%
Gopher Rockfish	34	40	17%
Olive Rockfish	52	40	–23%
Bocaccio	52	34	–35%
CA Sheephead	30	28	–8%
Leopard Shark	22	28	30%
Pacific Sanddab	20	26	33%
Starry Rockfish	29	21	–27%
Yellowtail Rockfish	56	19	–65%
Cabezon	22	15	–29%
China Rockfish	13	14	7%
Greenspotted Rockfish	13	10	–24%
Kelp Greenling	9.5	9.5	0%
Grass Rockfish	9.1	7.3	–20%
Black & Yellow Rockfish	3.4	5.9	75%
Flag Rockfish	7.8	5.5	–29%
SpeckledRockfish	4.9	5.2	6%
Other Rockfish	67	44	–34%
Total Groundfish	1292	945	–27%
Angler Trips			
Bottomfish Effort	734,000	798,000	8%

Rockfish species of concern yelloweye rockfish (0.7 t), cowcod (0.2 t) and canary rockfish (1.7 t) are included in the "Other" category.

(A+B1) – Fish caught and either identified or not available for identification

Data source: RecFIN

black rockfish, vermilion rockfish (*Sebastes miniatus*), lingcod, blue rockfish (*Sebastes mystinus*), and California scorpionfish (*Scorpaena guttata*). The same five species accounted for 56% of the total groundfish catch in 2007 although vermilion rockfish was the dominant species. Black rockfish was the dominant species caught in the north, followed by lingcod, vermilion rockfish, and blue rockfish. Blue rockfish was the dominant species caught on the central coast, followed by lingcod, vermilion rockfish, and black rockfish. California scorpionfish was the dominant species caught in southern California, followed by vermilion rockfish, bocaccio (*Sebastes paucispinis*), and California sheephead (*Semicossyphus pulcher*).

Yelloweye Rockfish Stock Assessment. The first yelloweye rockfish (*Sebastes ruberrimus*) stock assessment was completed in 2001 for the population along the coast of northern California and Oregon. The study concluded that the stock was approximately 7% of its unfished biomass and, as a result, was declared "overfished" by NMFS in 2002. Subsequent stock assessments in 2006 and 2007 also concluded that the stock was overfished and that rebuilding the stock to a sustainable level would take approximately 75 years. As a result of the 2002 overfished designation, increased regulations were put in place for the recreational and commercial fisheries to reduce the catch of yelloweye rockfish, including season, area, and depth restrictions. By 2003, yelloweye rockfish were not allowed to be retained by either recreational or commercial anglers and were only taken as bycatch.

Since 1969, when data first became available for yelloweye rockfish, commercial landings peaked in 1971

TABLE 5
Commercial landings of yelloweye rockfish (*Sebastes ruberrimus*) in metric tons with ex-vessel value and average price per pound, 1969–2008

Year	Harvest (t)	Ex-vessel Value	Average Price per Pound	Year	Harvest (t)	Ex-vessel Value	Average Price per Pound
1969	633	$91,588	$0.07	1989	23	$32,630	$0.66
1970	665	$110,436	$0.08	1990	39	$70,064	$0.81
1971	711	$119,342	$0.08	1991	39	$70,305	$0.81
1972	639	$125,412	$0.09	1992	29	$50,875	$0.79
1973	302	$99,643	$0.15	1993	18	$33,669	$0.84
1974	202	$88,859	$0.20	1994	26	$58,283	$1.03
1975	210	$109,293	$0.24	1995	30	$85,871	$1.28
1976	296	$182,306	$0.28	1996	45	$132,317	$1.33
1977	305	$225,448	$0.34	1997	42	$98,222	$1.06
1978	345	$302,653	$0.40	1998	17	$50,752	$1.33
1979	344	$345,969	$0.46	1999	10	$36,785	$1.74
1980	22	$20,760	$0.42	2000	3.3	$16,259	$2.23
1981	248	$279,725	$0.51	2001	3.8	$19,920	$2.36
1982	63	$29,961	$0.22	2002	0.07	$130	$0.89
1983	0.9	$468	$0.24	2003	0.01	$20	$0.91
1984	0.3	$235	$0.36	2004	0.02	$46	$1.07
1985	0.4	$243	$0.29	2005	0.02	$23	$0.50
1986	5.2	$8,828	$0.76	2006	0	$6	$0.61
1987	23	$31,779	$0.62	2007	0.18	$800	$2.00
1988	16	$22,627	$0.63	2008	0.02	$16	$0.30

Data Source: CFIS

TABLE 6
Recreational landings (in metric tons) of yelloweye rockfish (*Sebastes ruberrimus*).

Year	Harvest (t) (MRFSS)	Year	Harvest (t) (MRFSS)	Harvest (t) (CRFS)
1980	75.9	1995*	12.6	
1981	46.9	1996	12.5	
1982	103.8	1997	15.1	
1983	51	1998	5.8	
1984	80.8	1999	12.6	
1985	125.8	2000	7.5	
1986	65.5	2001	4.6	
1987	75.2	2002	2.1	
1988	57.5	2003	3.7	
1989	58.7	2004		0.8
1990	No Data	2005		1
1991	No Data	2006		1.1
1992	No Data	2007		3.8
1993*	8.5	2008		0.7
1994*	14.4			

Data not available for 1990 through 1992.
*CPFV mode data not available for central and northern California for 1993 through 1995.
Data source: RecFIN (MRFSS and CRFS)

when 711 t were landed (tab. 5). The highest ex-vessel value from the commercial yelloweye rockfish fishery occurred in 1979 with an approximate value of $345,969 (tab. 5). Yelloweye rockfish are primarily taken with hook-and-line gear.

An evaluation of both MRFSS and CRFS data suggests that landings of yelloweye rockfish peaked in 1985 with an estimated 125 t of fish landed (tab. 6). Landings decreased significantly once the non-retention regulation for yelloweye rockfish was put in place in 2003. In addition, CRFS estimates indicated that 99% of the total harvested catch came from boat-based recreational anglers. Since 1980, almost half of the catch has been landed on CPFVs and half from private and rental boats. The primary reason for such high catch values from the boat-based anglers is the average depth range for the species (18.2 to 549 m, 60 to 1,800 ft), which often makes them inaccessible to shore-based anglers.

Management History. Yelloweye rockfish became a federally designated groundfish in 1982 after the Council adopted the Pacific Coast Groundfish FMP. Since then, yelloweye rockfish have been managed under the joint jurisdiction of the state and federal governments. In 2004, the Council adopted a yelloweye rockfish rebuilding plan; since then, yelloweye rockfish has been managed with its own acceptable biological catch and optimum yield (OY). In the case of overfished species, the OY level is adjusted to rebuild the species population to a sustainable level while considering impacts of low harvest levels on fishing communities. Strict management measures in state and federal waters were adopted for both commercial and recreational user groups to prohibit retention and rebuild the stock as quickly as possible.

In 2007, the California recreational HG for yelloweye rockfish was exceeded despite early closures for the northern and north-central groundfish management areas. In 2008, the Department's in-season tracking model projected the HG for the recreational yelloweye rockfish fishery would be exceeded again if the season continued at the current rate. Since most of the yelloweye rockfish were caught in northern California, an emergency closure was instituted in September 2008 from the Oregon-California border to Point Arena (Mendocino County), which kept the final annual harvest below the HG.

California Spiny Lobster

The commercial and recreational seasons for harvesting the California spiny lobster, (*Panulirus interruptus*) occur from late September to the middle of March. Essential commercial fishery information is collected using fishermen-submitted logbooks and dealer-submitted landing receipts. Logbooks record location and date of catch, number of traps, and number of kept and released lobsters. Landing receipts record catch location, size of catch in pounds, and the price paid per pound. The recreational season is monitored through the use of a lobster report card introduced at the beginning of the 2008–09 recreational season and from data collected by CRFS samplers. Additional information on the recreational fishery was collected by an intercept survey, a nighttime extension to CRFS, during the first 10 weeks of the 2007–08 season.

Commercial Fishery. The commercial lobster fishery is a restricted access program with 204 lobster operator permits for 2008. Most (142) of these permits are transferable. While there have been no restrictions on the number of transferable permits that can be transferred since 1 April 2008, only 11 transfers took place in calendar year 2008. In 2008, the number of fishermen with operator permits that actually fished was 174, up from 169 the previous year. In the 2007–08 season, however, the number of active fishermen was 167, a decline from 176 fishermen during 2006–07.

Currently, there are no restrictions on the amount of lobster that permittees can land or the number of traps they can use. Traps are generally set along depth contours in the vicinity of kelp beds along the mainland and at all the Channel Islands. Typically, between 100 and 300 traps are set at a time although those with larger boats or a crewmember may set more. Soak times in 2007–08 averaged three days. The total number of trap pulls in the 2007–08 season was estimated at 808,000 resulting in a catch of approximately 1.7 million lobsters, of which 27% were retained. This translates to a preliminary landing weight of approximately 306 t. This effort and catch was lower than during the 2006–07 sea-

Figure 6. California landings of California spiny lobster (*Panulirus interruptus*), 1916–2008.

son which had 852,000 trap pulls, an approximate catch of 1.9 million lobsters with 31% retained, and a landing weight of 398 t. By calendar year, however, 335 t was landed in 2008, 35 t more than in 2007 (fig. 6). While substantially lower than the recent peak of 403 t in 2006, the 2008 landing total continues a trend of 300 t, or more, lobsters landed per calendar year since 2000.

Approximately 42% of the total 2007–08 landings (127 t) occurred in the first month (October) of the season, with San Diego County accounting for 41% of that month's take; Santa Barbara/Ventura counties had the lowest first month landings at 25% (32 t). Interestingly, 23% of the total landings for the 2007–08 season, by weight, occurred along Point Loma in San Diego County.

The median ex-vessel price for both calendar year 2008 and the 2007–08 season was $24.25/kg ($11.00/lb) and ranged from $19.84/kg ($9.00/lb) to $27.56/kg ($12.50/lb). Overall, the ex-vessel value of the lobster fishery was $7.91 million in calendar year 2008, up from the $7.32 million in 2007, and approaching the decadal high of $8.06 million set in 2006. The ex-vessel value of the 2007–08 lobster season was $7.22 million. Point Loma landings had the highest ex-vessel value at $1.58 million representing 22% of the total season value.

Recreational Fishery. Recreational fishermen are allowed to catch lobster by hand when snorkeling or scuba diving, or by using baited hoop nets. Up to five baited hoop nets per person, with a maximum of ten hoop nets per boat, can be used. There is a daily bag and possession limit of seven lobsters per fisherman. In both the recreational fishery as well as the commercial fishery, lobsters must exceed a carapace length of 82.6 mm (3.25 in.) to be kept. A 1992 Department creel survey involving four sites in San Diego and Ventura counties during the first two weekends of the season revealed that approximately 80% of the interviewed lobster fishermen used scuba gear to catch lobsters; 20% used hoop nets. A more recent creel survey was conducted during the first 10 weeks of the 2007–08 lobster season. At the same 1992 survey sites, using data from the first two weekends, the 2007 creel survey found the opposite; approximately 82% of the fishermen used hoop nets while only 20% used scuba gear. Recent years have seen the introduction of a more efficient hoop net into the fishery which a Department study showed can catch 57% more lobster than a traditional hoop net with the same effort. During the 2007–08 season, the traditional hoop nets were still responsible for catching more lobsters, although in Santa Barbara/Ventura counties the catch was evenly split between the two types of hoop nets.

A total of 2,833 fishermen were interviewed during the 2007 creel survey. Of these, most did not catch legal-size lobsters. Of those that did, only 24 (<1%) were found with the bag limit of seven lobsters, and 21 (88%) of these occurred on private boats. About 81% of the lobsters caught were below the legal size limit and released.

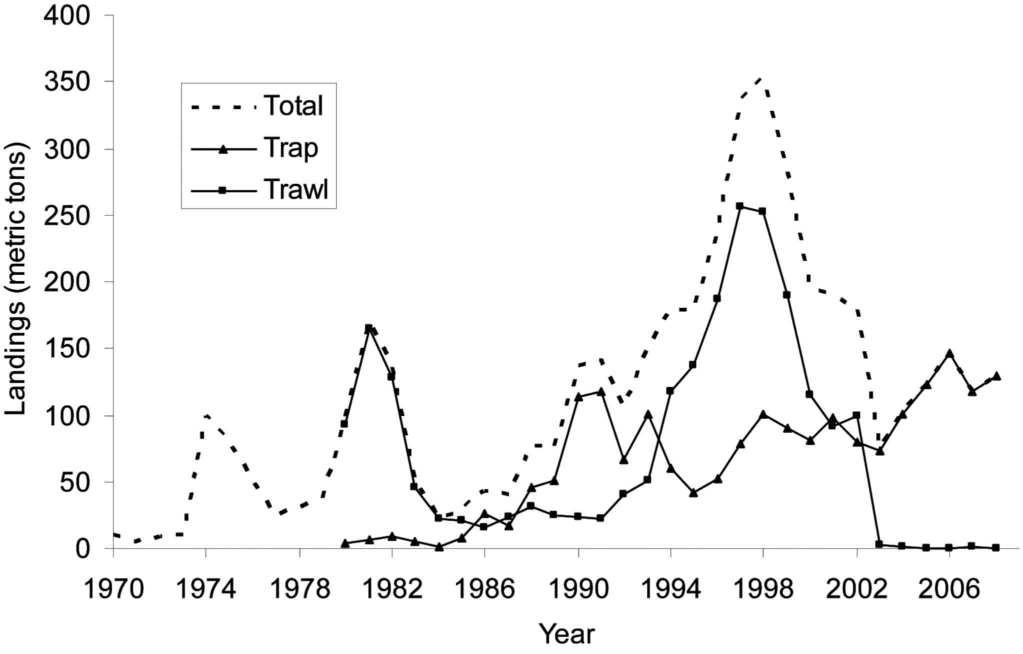

Figure 7. California landings of spot prawn (*Pandalus platyceros*) by gear type, 1970–2008.

Overwhelmingly, San Diego County accounted for the most effort (recorded as hours fished) in southern California (64% of the total hours) followed by Los Angeles/Orange counties (25%) and Santa Barbara/Ventura counties (11%). Interestingly, the number of lobsters kept per hour was highest in Santa Barbara/Ventura counties at about 0.5 lobster kept per hour fished while the other regions were about half that catch rate. Lobsters ranged in size from 58 mm (2.3 in.) to 183 mm (7.2 in.) carapace length and the study indicated that the highest number of lobster caught are just at the legal size limit of 82.6 mm (3.3 in.).

A lobster report card was introduced for the 2008–09 recreational season that records the time, location, gear, and retained catch size by outing for anyone fishing for lobster. Approximately 25,000 cards were sold at the beginning of the season, with about 5,000 completed cards returned to date. The information from the first half of the 2008–09 season is currently being analyzed.

Spot Prawn

Preliminary 2008 spot prawn (*Pandalus platyceros*) landings were 130 t, a 9% increase from 2007 (118 t) (fig. 7). 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 prohibited due to the bycatch of rockfish, particularly bocaccio an overfished species. Consequently, 2003 spot prawn landings were the lowest since 1987 when trapping was just getting underway in southern California. Current harvest levels are well below those of the mid-to-late 1990s and appear to be sustainable.

Spot prawn is currently caught only with trap gear, although a small amount shows up as bycatch in the ridgeback trawl fishery (0.5 t). Spot prawn traps are required to be made of mesh with a minimum inside measurement of 2.22 × 2.22 cm (7/8 × 7/8 in). The traps may not exceed 1.8 m (6 ft) in any dimension. The baited traps are fished in strings at depths of 174 to 302 m (571 to 991 ft) along submarine canyons or shelf breaks. Each string consists of a groundline with anchors and a buoy at one or both ends, and 10 to 30 traps attached. No other species may be taken in a prawn trap, so all bycatch is returned to the water immediately.

A two-tiered restricted access trap vessel permit program was initiated in 2002. Tier 1 permittees may use up to 500 traps, unless fishing in state waters north of Point Arguello where they are only allowed to use 300 traps. Eighteen trap vessel owners originally qualified and purchased these permits, and 17 remained when they became transferable on 1 April 2005. Three permits have been sold on the open market for approximately $200,000 each. The Department receives a transfer fee of $50.00 when a permit is sold.

Tier 2 vessel permittees made a smaller number of qualifying trap landings, and are limited to an annual harvest quota of just over 2 t. Permittees may use no more than 150 traps and the permits are non-transferable. Initially there were six permittees, but only three Tier 2 permittees remain.

When the use of trawl gear for the take of spot prawn was prohibited, the Commission directed the Department to develop a conversion program for the trawl fleet. The

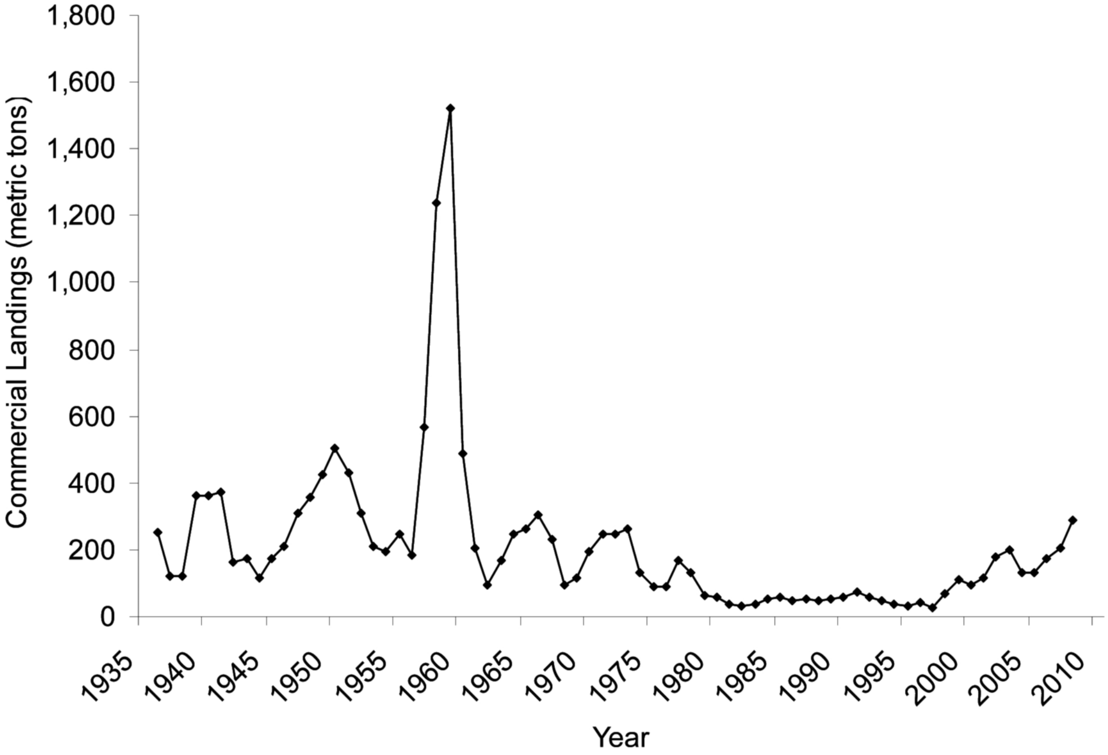

Figure 8. California commercial landing of white seabass (*Atractoscion nobilis*), 1936–2008. Note: Fish caught in US waters only (does not include fish caught in Mexico and landed in California).

conversion program went into effect in 2005, which allowed the owners of 12 former spot prawn trawl vessels to purchase Tier 3 spot prawn trap vessel permits in 2005. Tier 3 permittees have the same restrictions as Tier 1 permittees although the permits are non-transferable. Ten Tier 3 permittees remain. In 2008, the fee for the Tier 3 permit was $1,184.75, whereas, both Tier 1 and Tier 2 vessel permits were $296.

In 2008, 19 trap permittees landed spot prawn. Four of the 19 permittees fished in the vicinity of Monterey Bay, and the remaining vessels fished in southern California, frequently off one of the Channel Islands. Fifteen of the 17 Tier 1 trappers landed 87% of the catch with each vessel averaging 7.5 t. All three Tier 2 fishermen fished, and only one of the Tier 3 permittees went fishing. Most of the Tier 3 permittees have not had the funds necessary to purchase either a vessel more suitable for trapping, or the traps and associated ground tackle. A 0.023 t 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.

Almost all harvested spot prawn are sold live, with ex-vessel prices ranging from $22 to $31/kg ($10.00 to $14.00/lb). Fresh dead spot prawn generally sell for half the price of live. Most trap permittees have invested in live tanks and chillers on their vessels to keep the prawn in top condition for the live market.

The trap fishery in southern California (south of Point Arguello) is closed from 1 November to 31 January to provide protection for ovigerous 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.

White Seabass

The white seabass (*Atractoscion nobilis*) is the largest member of the Sciaenid family found in California waters. In addition to being a popular sport fish, white seabass are also targeted by a commercial fishery. The commercial white seabass fishery landed 291 t in 2008 (fig. 8), a 41% increase from the 2007 total of 207 t. Recreational landings decreased by 11% to 51 t in 2008 from the previous year's total of 57 t. The RecFIN estimates prior to 2004 are from a different survey and are not directly comparable to the estimates from the CRFS. However, historical trends in the recreational catch of white seabass can be determined from CPFV logbook data (fig. 9). The combined commercial and recreational catch for 2008 was 342 t.

There have been commercial and recreational fisheries for white seabass in California since the 1890s. Historically, commercial landings have fluctuated widely, including the landings of white seabass taken in Mexican waters by California commercial fishermen. Before 1982,

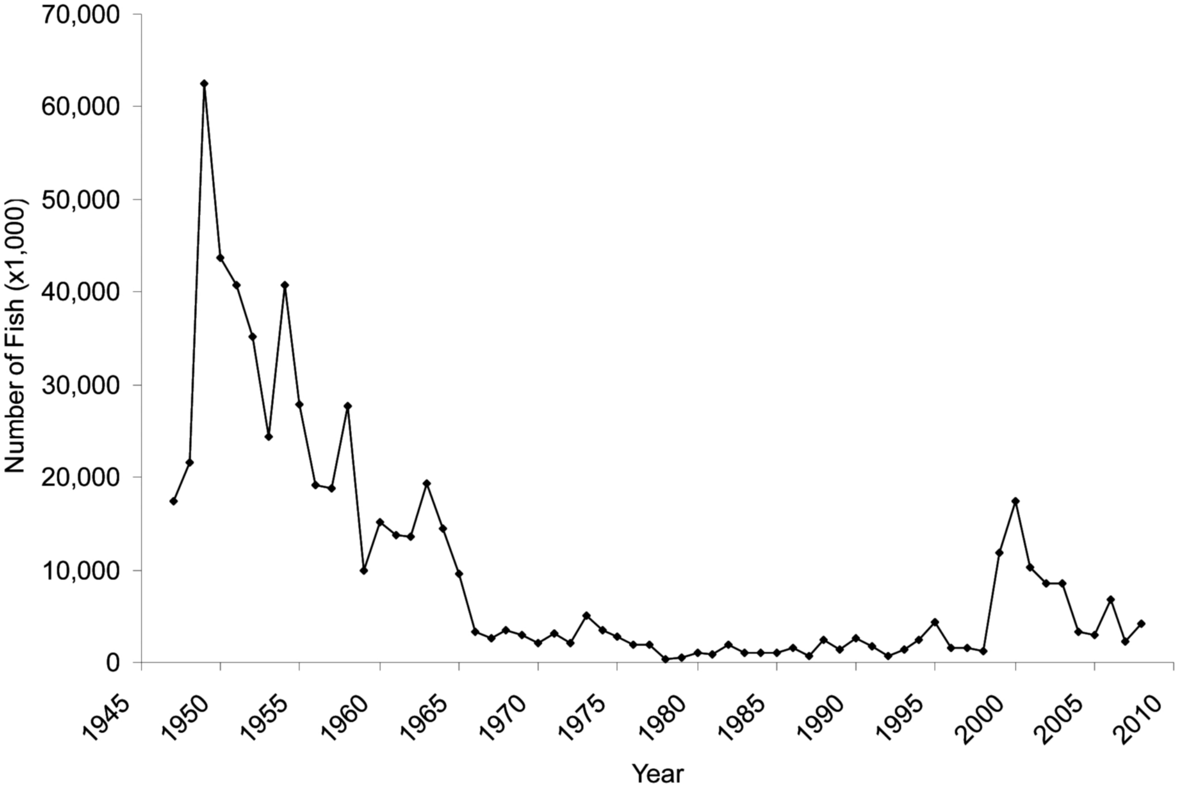

Figure 9. California recreational catch (in numbers of fish) of white seabass (*Atractoscion nobilis*) from CPFV, 1947–2008. Notes: Fish caught in US waters only (does not include fish caught in Mexico and landed in California), 1947–2008 recreational catches from Commercial Passenger Fishing Vessel (CPFV) logbook database.

the white seabass commercial take in Mexican waters comprised from 1% in 1959 to 89% in 1981 of California's white seabass annual landings (fig. 10). Since then, the Mexican government has prohibited access permits to the U.S. commercial fleet. Beginning in 1994, the use of set and drift gill nets within three nautical miles (3.5 mi) of the mainland shore from Point Arguello to the U.S.-Mexico border and in waters less than 128 m (70 fathoms) or within 0.9 nautical miles (1 mi) (whichever is less) of the Channel Islands was prohibited. In April 2002, the use of gill and trammel nets in depths of 110 m (60 fathoms) or less was prohibited from Point Reyes (approximate latitude 38.0°N) to Point Arguello (approximate latitude 34.6°N). Despite restrictions, most commercial white seabass landings are still taken with set and drift gill nets. In 2008, set and drift gill nets accounted for 98% of the commercial landings by weight and less than 1% of commercial white seabass landings were from north of Point Arguello. White seabass have a minimum legal size limit of 710 mm (28 in) TL.

The commercial fishery for white seabass is closed between Point Conception (approximate latitude 34.45°N) and the U.S.-Mexico border from 15 March to 15 June, with the exception of one fish not less than the minimum size limit may be taken, possessed, or sold by a vessel each day if taken incidental to gill and trammel net fishing operations. In 2008, the average ex-vessel value paid by dealers was $6.37/kg ($2.89/lb) and the total ex-vessel value was $1.5 million, approximately 30% more than in 2007.

The recreational fishery for white seabass occurs almost entirely (97%) south of Point Arguello (approximate latitude 34.6°N). The fishery is open all year, but the majority of the recreational take occurs between March and September. White seabass have a minimum legal size limit of 710 mm (28 in.), and the daily bag limit is three fish, except from 15 March through 15 June when the daily bag limit is one fish. Most fish are caught by hook-and-line anglers onboard CPFVs and private boats.

In 1982, the California Legislature established the Ocean Resources Enhancement and Hatchery Program (OREHP). The legislation was adopted to fund research into the artificial propagation of marine finfish species whose populations had become depleted. The ultimate goal of the legislation is to enhance populations of marine finfish species important to California for their recreational and commercial fishing value. Initially, research was focused on California halibut and white seabass; however, white seabass was eventually chosen as the primary species to focus on because of the depressed con-

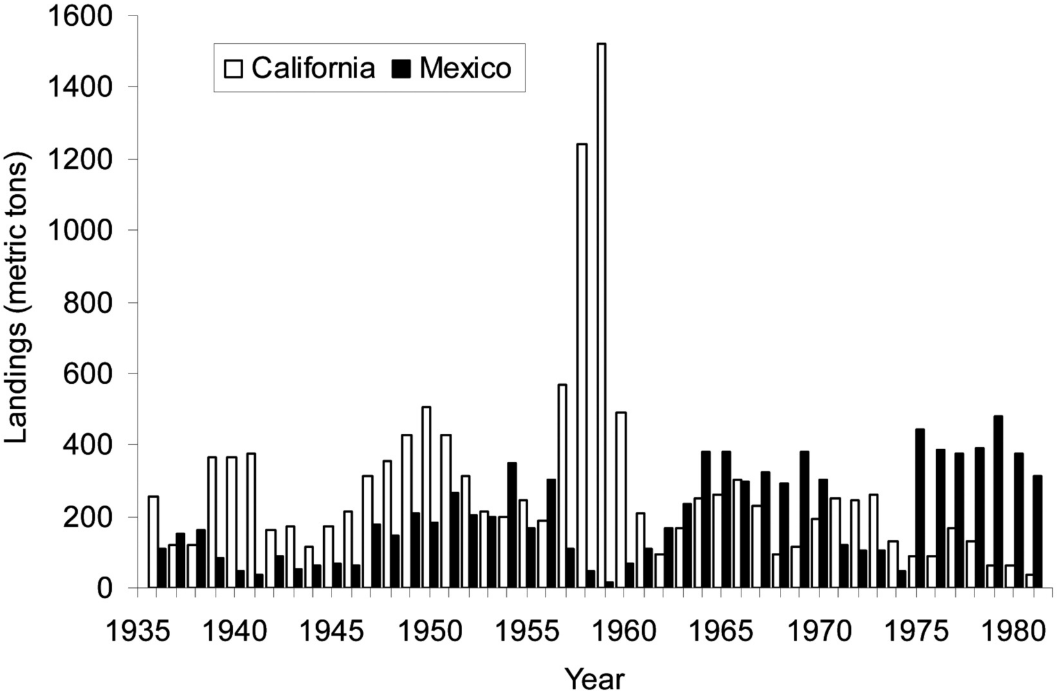

Figure 10. California and Mexico commercial landings of white seabass (*Atractoscion nobilis*), 1936–1981. Note: Fish caught in US waters only (does not include fish caught in Mexico and landed in California).

dition of the stock at the time and its higher value to recreational and commercial fishermen.

The Department manages the OREHP with the assistance of an advisory panel that consists of academic and management agency scientists, representatives of both commercial and recreational fishing groups, and the aquaculture industry. The program is funded through the sale of recreational and commercial marine enhancement stamps for all saltwater anglers south of Point Arguello. In 1995, the OREHP completed construction of the Leon Raymond Hubbard, Jr. Marine Fish Hatchery in Carlsbad, California. The primary function of the hatchery, operated by the Hubbs-Sea World Research Institute (HSWRI), is to provide juvenile white seabass, approximately 100 mm TL (3.9 in.), to growout facilities operated by volunteer fishermen. The hatchery is designed to produce 350,000 juvenile white seabass; however, the current release limit, which is imposed by the California Coastal Commission as a condition of the Coastal Development Permits for the growout facilities, is set at 125,000 fish per calendar year.

Currently, there are 13 growout facilities located in bays and marinas from Santa Barbara to San Diego in southern California. The growout facilities rear juvenile white seabass to 200 to 250 mm (7.8 to 9.8 in.) TL before releasing them at or near the growout site. In 2008, 58,484 hatchery-raised white seabass were released, approximately 29% of last year's release of 199,682 fish. This decline in production was due to disease issues within the hatchery and growout facilities. Since 1986, over 1.5 million white seabass, each implanted with a coded wire tag (CWT), have been released from the OREHP facilities.

Since the mid-to-late 1980s, the OREHP has contracted with researchers to develop juvenile and adult gill net sampling programs to assess the proportion of hatchery-raised fish to the wild population using coded wire tagged fish. Since the inception of both programs, 1,400 hatchery-raised juvenile white seabass have been recovered in the juvenile gill net studies while 125 tagged adult white seabass (legal-size) have been recovered from the recreational and commercial fisheries. The results of both the juvenile and adult sampling programs will be used in evaluating the success of the OREHP.

To manage the state's commercial and recreational fisheries for white seabass, the Commission adopted the White Seabass Fishery Management Plan (WSFMP) in 1996. To implement the WSFMP in accordance with the Marine Life Management Act adopted in 1998, the Commission adopted regulations in 2002 to establish a fishing season of 1 September through 31 August of the following year. The Commission also adopted an OY in 2002 based on an MSY proxy of the unfished biomass, and currently set at 540 t. The OY has never been reached since its implementation, but came close in the 2001–02 fishing season when it reached 530 t. In the 2007–08 fishing season, the total recreational and commercial harvest was 344 t, or 64% of the allowable catch.

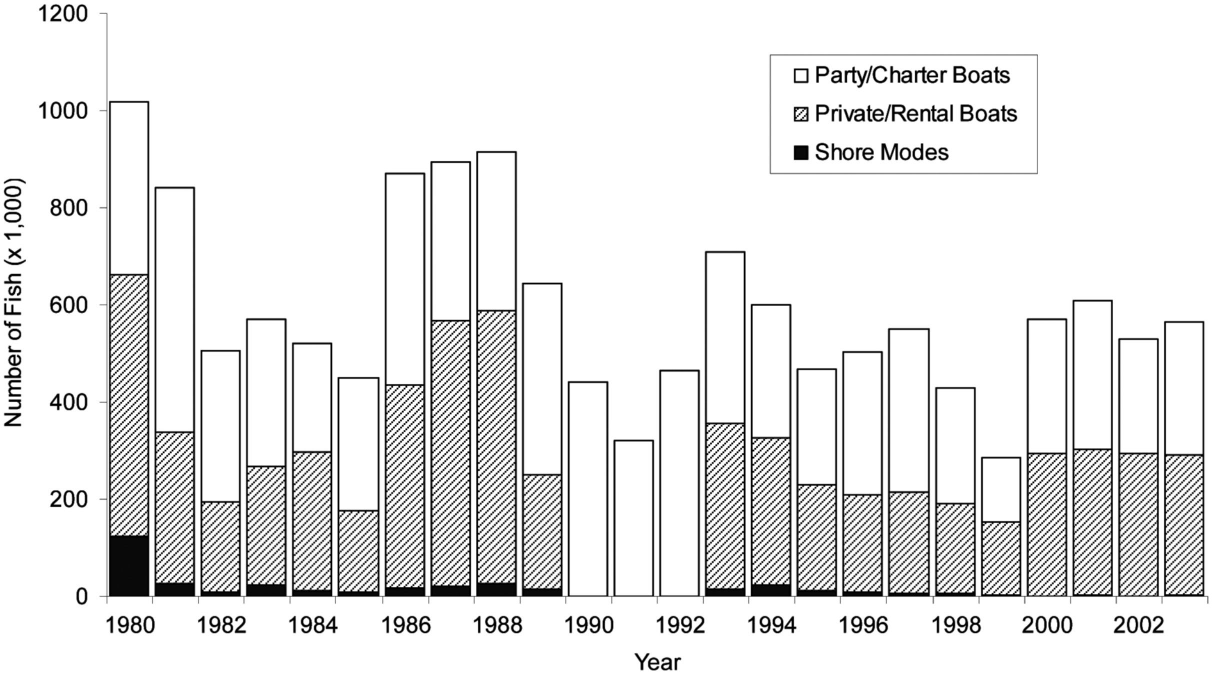

Figure 11. California recreational landings of kelp bass (*Paralabrax clathratus*) as reported in the Marine Recreational Fisheries Statistical Survey (MRFSS) by three different fishing modes, 1980–2003.

The WSFMP includes a provision for annual monitoring and assessment of the white seabass fisheries.

Kelp Bass

The kelp bass (*Paralabrax clathratus*) commonly referred to as calico bass, is one of the most popular species caught by recreational anglers in southern California. Kelp bass are found in nearshore waters and have historically ranged from the Washington/Oregon border in the north to Magdalena Bay, Baja California, Mexico in the south; however, their occurrence is rare north of Point Conception. Kelp bass live in relatively shallow water (typically less than 50 m) and tend to be associated with rocky structures and kelp. The best time of year to catch kelp bass is from May through September when the fish tend to feed more aggressively. Kelp bass are known to reach 721 mm (28.4 in) and can weigh up to 6.6 kg (14.5 lb).

In the first half of the twentieth century, kelp bass were targeted by both commercial and recreational fishermen. At that time, they were recorded on landing receipts and logbooks in a general "rock bass" category which included barred sand bass (*Paralabrax nebulifer*) and spotted sand bass (*Paralabrax maculatofasciatus*). In 1953, it became illegal to fish for kelp bass commercially in California due to a sharp decline in annual landings. Recreational anglers were still permitted to take kelp bass, but in 1959 a minimum size limit of 12 in (305 mm) TL was imposed. This minimum size limit is still in effect today, as well as a bag limit that allows a maximum of 10 kelp bass per day to be taken or possessed by each licensed angler.

The MRFSS and CRFS has collected historical size and total estimated catch data for kelp bass from the private/rental boat, beach-and-bank, and man-made structure fishing methods, and historical size data from the CPFV fishery. Total estimated catch data for CPFVs are available from CPFV logbooks. MRFSS provided data from 1980 to 2003 (fig. 11, tab.7), with the exception of 1990–92, and CRFS has provided data from 2004 to the present (fig. 12, tab. 7). Survey methods are not comparable. MRFSS data and CPFV logbook data in aggregate show an overall decline in number of fish caught by recreational anglers since 1980 when an estimated 1,019,000 kelp bass were caught. CRFS and CPFV logbook data estimated that 256,000 kelp bass were caught by recreational anglers in 2008, a decrease of 16% from 2007. Shore-based fishing modes, which include beaches, banks, and man-made structures, comprised only 4% of the recreational kelp bass catch in 2008, while CPFVs and private/rental boats comprised the remaining 96%. From 1999 to 2008 MRFSS and CRFS samplers measured over 52,000 kelp bass with an average TL of 365 mm (14.4 in.). In 2008, average TL of approximately 4,800 kelp bass measured was 366 mm (14.4 in.), slightly less than the 373 mm (14.7 in.) average TL from approximately 4,200 fish in 2007.

CPFV logbook data are available from 1935 to the present, but kelp bass were not differentiated from the other "rock basses" until 1975. CPFV logbook data in-

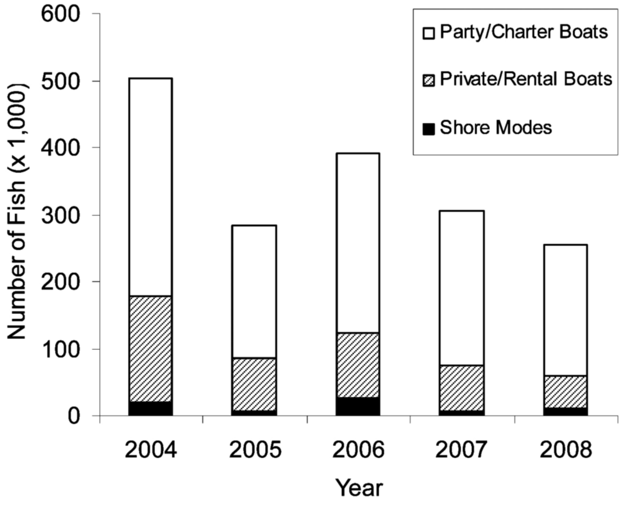

Figure 12. California recreational landings of kelp bass (*Paralabrax clathratus*) as reported in the California Recreational Fisheries Survey (CRFS) by three different fishing modes, 2004–08.

dicate annual kelp bass catches from 1980 to the present have fluctuated but have declined overall since 1992 (fig. 13). In general, the number of CPFV anglers on trips in which kelp bass were caught also declined, indicating that the average catch per angler has remained fairly consistent during that time period. The number of CPFV anglers participating in trips where kelp bass were caught peaked during the major El Niño event of 1997–98, and

TABLE 7

California estimated annual kelp bass (*Paralabrax clathratus*) recreational catch in metric tons, 1980–2008.

Year	Metric Tons (mt)
1980	726.4
1981	588.4
1982	308.5
1983	372.0
1984	407.1
1985	246.0
1986	567.6
1987	606.6
1988	564.5
1989	373.0
1993	562.0
1994	435.0
1995	354.2
1996	335.4
1997	363.6
1998	294.8
1999	192.8
2000	415.2
2001	389.0
2002	330.5
2003	378.4
Values above and below are not comparable due to different survey methods	
2004	325.4
2005	184.2
2006	261.8
2007	201.0
2008	162.6

Note: recreational data from MRFSS were unavailable from 1990-1992.

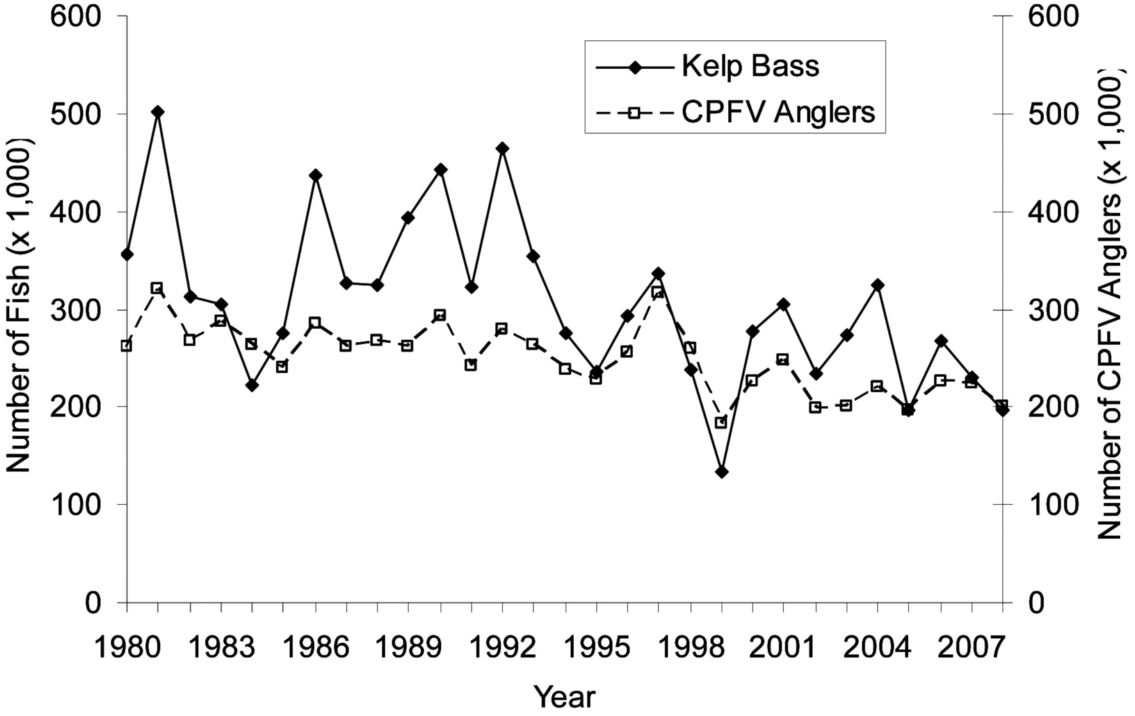

Figure 13. California recreational landings of kelp bass (*Paralabrax clathratus*) as reported in Commercial Passenger Fishing Vessel (CPFV) logbooks, 1980–2008.

TABLE 8
Annual number of kelp bass (*Paralabrax clathratus*) caught by California commercial passenger fishing vessels (CPFVs) statewide by port for 2008 and 2007 and 10-year average (1999–2008).

	2008		2007		10-Year Average (1999-2008)	
Port Name	No. Fish Caught	% Total	No. Fish Caught	% Total	No. Fish Caught	% Total
Oxnard/Channel Islands	16,734	8.5	5,922	2.6	15,749	6.5
Redondo Beach	14,364	7.3	16,233	7.1	17,433	7.1
San Pedro	33,957	17.3	35,902	15.6	39,234	16.1
Long Beach	24,935	12.7	37,600	16.4	34,453	14.1
Newport Beach	17,541	8.9	20,391	8.9	22,494	9.2
Balboa	3,118	1.6	8,380	3.6	5,183	2.1
Dana Point	25,379	12.9	30,708	13.4	30,423	12.5
Oceanside	8,767	4.5	9,342	4.1	9,385	3.8
Mission Bay	17,230	8.8	28,494	12.4	30,755	12.6
San Diego	23,329	11.9	30,533	13.3	25,164	10.3
Other	11,043	5.6	6,334	2.8	13,677	5.6
Total CPFV Catch	196,397	100.0	229,839	100.0	243,950	100.0

Data Source: CFIS

TABLE 9
Annual commercial landings (metric tons) and value (dollars) of common thresher shark (*Alopias vulpinus*) into California port complexes for 2007 and 2008 and ten year average (1999–2008).

	2008		2007		10-Year Average (1999-2008)	
Area	Landings (t)	Value ($)	Landings (t)	Value ($)	Landings (t)	Value ($)
San Francisco	<0.1	50	0.9	810	0.4	546
Monterey	1.5	2,399	3.6	3,594	3.7	5,806
Santa Barbara	75.1	126,626	65.7	108,079	60.7	90,387
Los Angeles	21.7	40,625	56.2	86,498	65.8	100,247
San Diego	48.7	109,962	77.1	137,912	97	164,289
Total Landings	147	279,662	203.5	336,893	227.5	361,275

after a substantial decline during the next two years fluctuated with no trend. Since 1980, a peak of 502,000 kelp bass were caught by CPFV anglers in 1981 and a low of 133,000 were caught in 1999. From 2007 to 2008 a 15% decline in CPFV catch was observed.

Kelp bass have consistently ranked among the top ten species or species groups caught by southern California CPFV anglers during the past 20 years. In terms of number of fish caught in 2008, kelp bass ranked second, with rockfish as an aggregate ranking first (only some rockfish are required to be reported by species). On average, over the past 10 years, the port of San Pedro had the highest number of kelp bass caught by CPFVs (tab. 8). In 2008, 17% (33,957) of the kelp bass caught in California were brought into San Pedro. In 2007, however, Long Beach was the number one port for kelp bass catch with 16% (37,600). Other major ports for kelp bass include Dana Point, Mission Bay, San Diego, and Newport Beach.

Thresher Shark

The common thresher shark (*Alopias vulpinus*) is the most common commercially-landed shark in California. The common thresher sharks are large pelagic sharks whose most defining characteristic is the enormous upper lobe of the tail, which can be up to half their TL, and is used to stun their prey. They can be differentiated from two other thresher sharks that occur in California, the bigeye thresher (*A. superciliosus*) and the pelagic thresher (*A. pelagicus*) by the white belly markings extending over the top of the large pectoral fins and a slight bronzy-green iridescence to the skin. Common thresher sharks have a world-wide distribution in temperate seas and are found in the Mediterranean Sea and the Atlantic, Pacific, and Indian Oceans. They tend to be most common over continental shelves, associated with areas of high productivity where concentrations of the small schooling organisms that make up most of their diet are found. Young threshers tend to remain within three miles of the coast in their early years and as they grow larger, range much farther offshore. Migratory patterns inferred by seasonal catches seem to indicate that adult threshers move north from Baja California in the spring, into the Southern California Bight, where "pupping" is thought to occur.

Commercial Fishery. Although primarily targeted using large-mesh drift gillnets (73% of total) and hook-and-line gear (6%), thresher sharks are also caught incidentally with small mesh gillnets (21%) and occasionally by harpoon. Commercial landings declined 28% in 2008 to 147 t (round weight) from 204 t in 2007 (tab. 9). The ex-vessel value of thresher shark totaled $279,661 with an average price of $3.24/kg ($1.47/lb), down from $336,894 in 2007, with the average price at $2.81/kg ($1.28/lb). Much of the commercial fishing for thresher shark occurs in the Southern California Bight, with the highest average proportion of landings over the last ten years occurring in the San Diego port complex. In 2008, however, the greatest amount of landings occurred in the Santa Barbara port complex, followed by San Diego and then Los Angeles/Orange Counties (tab. 10).

TABLE 10
Estimated recreational catch (A+B1) of common thresher shark (*Alopias vulpinus*) in metric tons by fishing modes as sampled in the Marine Recreational Fisheries Statistics Survey (MRFSS), 1980–2003 and the California Recreational Fisheries Survey (CRFS), 2004–08.

Year	Man Made Beach/Bank	Charter Vessel	Private/ Rental Vessel	Total of All Modes	Percent Private/ Rental Vessel
1980	0.0	1.8	0.0	1.8	0%
1982	0.0	0.0	4.4	4.4	100%
1983	0.5	0.0	38.5	39.1	99%
1984	0.0	0.0	39.7	39.7	100%
1985	0.0	0.0	4.9	5.7	86%
1986	0.0	0.0	25.5	25.5	100%
1987	0.0	0.0	100.5	100.5	100%
1988	0.0	4.8	17.2	21.9	78%
1993	0.2	0.0	10.3	10.5	98%
1994	0.0	0.0	33.5	33.5	100%
1995	0.0	0.0	19.6	19.6	100%
1996	0.0	0.0	4.3	4.3	100%
1997	0.0	0.0	11.7	11.7	100%
1998	3.8	0.0	39.2	42.9	91%
1999	0.0	2.7	13.1	15.8	83%
2000	5.7	0.0	7.9	13.6	58%
2001	0.0	0.0	20.6	20.6	100%
2002	0.0	0.0	3.2	3.2	100%
2003	2.5	0.0	24.9	27.4	91%
Sub-Total	**12.7**	**9.2**	**419.0**	**441.8**	
Avg. 80-03	**1.3**	**0.9**	**41.9**	**44.2**	**89%**
2004	0.0	0.5	2.8	3.3	85%
2005	0.0	0.0	11.6	11.6	100%
2006	7.1	0.0	15.6	22.7	69%
2007	25.9	0.6	25.3	51.8	49%
2008	6.8	0.0	28.8	35.6	90%
Sub-Total	**39.8**	**1.1**	**84.1**	**125.0**	
Avg. 04-08	**8.0**	**0.2**	**16.8**	**25.0**	**79%**
Total	**52.5**	**10.3**	**503.1**	**566.8**	

Note: recreational data from MRFSS were unavailable from 1981, 1989–92.

Prior to 1977, all sharks were reported in one market category and not separated by species, and it is assumed threshers were caught as "bycatch" in gears at levels similar to or greater than today. The first significant fishery for thresher sharks began in the late 1970s to early 1980s when drift-gillnet fishermen began to target them close to the southern California coastline. The fishery expanded rapidly and, due to overfishing concerns, the Department began an observer program, monitored landings, and implemented a logbook program. A limited entry permit program for drift gear was initiated in 1982, with permits issued to fishermen rather than boats to prevent false inflation in value. The drift-gillnet fishery for thresher sharks peaked in 1981 when 113 drift gillnet boats landed nearly 446 t. However, total landings using all gears were highest the following year with a total of more than 1,800 t taken by all gears (fig. 14).

By the late 1980s, research monitoring of the commercial catch indicated that entire size classes were no longer being caught. Legislation was enacted for a series of time/area closures in order to protect the shark resource. The objectives of these closures were threefold: (1) to protect large females who moved into the Southern

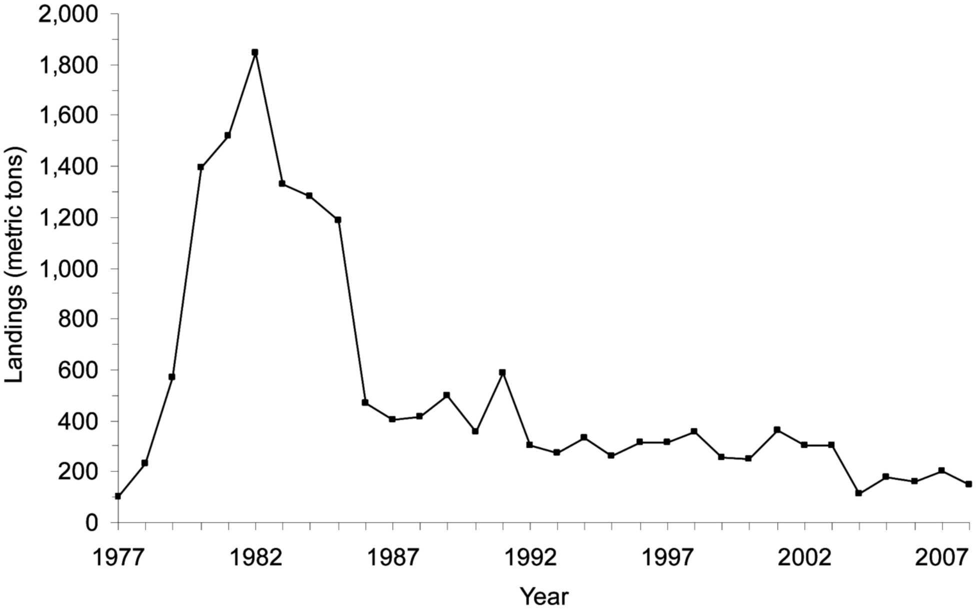

Figure 14. California commercial landings of common thresher shark (*Alopias vulpinus*), 1977–2008. Notes: Data sources are Department Catch Bulletins from 1977 to 1985 and CFIS landing receipt database from 1986 to 2008.

California Bight during their pupping season, (2) to prevent interactions with marine mammals, sea turtles, and sea birds, and (3) to prevent conflicts with harpoon fisheries. Several revisions to the time and area closures resulted in the fishery being completely closed between 1 February and 30 April, and closed within 75 miles of the coast from 1 May through 14 August.

In the early 1980s, most drift-gillnet vessels switched to swordfish as their primary target species. Thresher sharks, along with shortfin mako sharks (*Isurus oxyrinchus*), were targeted secondarily and landings of threshers began to decline (fig. 14). In 1990, a California voter referendum banned gillnets in state waters (within three miles of shore). A further federal closure to protect leatherback turtles (*Dermochelys coriacea*) from Point Conception to central Oregon from 15 August to 31 October was enacted in 2001. In addition, during El Niño conditions, the area south of Point Conception is closed to drift gillnet fishing 15–31 August and for January to protect loggerhead turtles (*Caretta caretta*). These closures have caused a further drop-off in thresher shark landings since being enacted and landings of thresher sharks have averaged 161 t since 2004 (fig. 14). At present, the only requirement for purchasing a drift gillnet permit is possession of one during the preceding season; there is no landing requirement. Currently, there are 83 drift gillnet permittees and only about half of those are actively fishing.

Thresher sharks are also taken by other commercial gears, including hook-and-line, small mesh gillnets, and harpoon. Small mesh gillnets include set nets targeting California halibut and drift nets targeting barracuda (*Sphyraena* spp.) and white seabass. Small mesh drift gillnets, mesh 8 in (203 mm) or smaller, targeting white seabass and barracuda are not required to have a drift gillnet permit, however state regulations limit possession to no more than two threshers along with 10 barracuda or five white seabass, while federal regulations have a limit of 10 highly migratory species (HMS), except for swordfish (*Xiphias gladius*). In 1996, a ban on landing detached shark fins became effective for all commercial fishing gears. Because of their size, threshers are the only exception to this rule; however, the fins must match a corresponding carcass.

Recreational Fishery. Thresher sharks have long been a desired species for recreational fishermen, and considered a prized fighting fish. California sportfishing regulations impose a two fish per day per angler limit on thresher sharks. This is cumulative for multi-day trips and most anglers seldom fill bag limits. Boat limits are in effect for multiple anglers per boat, with no more than the bag limit for each of the number of licensed anglers per boat. Again, these limits are seldom filled. If filleted at sea, a one-inch patch of skin must be left on the fillets. In recent years, interest in thresher shark has increased as other sportfishing species become more heavily regulated, and some fishing areas are closed to protect other fish species. Many shark anglers practice a catch and release ethic. However, the survival of these released fish, often caught using a species specific tactic of tail-hooking, may be much lower than previously thought. Research is currently underway to determine specific survival rates of tail-hooked sharks. Alternative gears, which have a higher probability of hooking the shark in the mouth rather than the tail, are also being studied.

Recreational thresher shark catches are highest May through August, for both kept and released fish. Most recreational thresher shark take occurs in the private/rental boat mode (89% in MRFSS data, 77% in CRFS data) (tab. 10). In 14 of the 24 (58%) sampling years since 1980, the estimated number of threshers released alive has been greater than or equivalent to those kept. Since 2004, estimates of the tonnage of fish released alive have been available; in four of the five sampling years the estimated tonnage of fish released has also been greater than or equivalent to those kept. Threshers are often taken incidentally while fishermen are targeting other species. Those taken in northern California were all incidental to salmon or halibut recreational fishing trips, while in southern California, 69% were caught on trips targeting threshers and incidentally caught on halibut, yellowtail, and barred sand bass trips. CPFV logs indicate that the take of thresher sharks aboard their vessels is much less than that taken by anglers fishing from private boats. For the last fifteen years, the CPFV take of threshers averaged about 40 fish a year with a high of 163 fish during the El Niño of 1993.

Management History. The Council adopted the Highly Migratory Species Fishery Management Plan (HMS FMP) in February 2005, putting thresher shark under federal management, although California regulations were used as a model for most HMS species. The HMS FMP establishes a biennial management cycle in which measures to be implemented are introduced in June and, if approved, implemented the following April. For thresher sharks, a harvest guideline of 340 t was established for total commercial and recreational catch. The HMS FMP identified priority research needs for additional life history information for thresher shark including: (1) identify stock structure and boundaries of the populations and, where they interact with other populations, the seasonal migration patterns for feeding and reproduction and life stages vulnerable to fisheries; (2) determine ages and growth rates including comparisons to other areas; and (3) determine maturity and reproductive schedules. Preliminary assessment analyses indicated that West Coast drift-gillnet fishery catch and catch-per-unit-effort were increasing from the lows of the early 1990s; from this it was inferred that the pop-

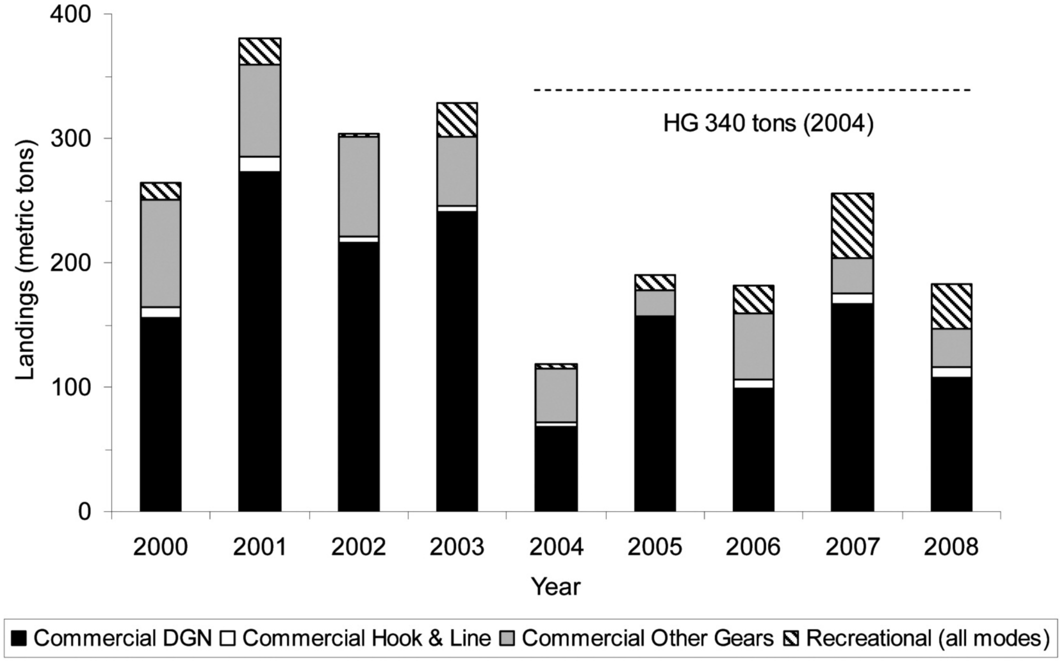

Figure 15. California landings of common thresher (*Alopias vulpinus*) by commercial gear type and by the recreational fishery compared to the harvest guideline adopted in 2004. Notes: Commercial landings are from CFIS converted from pounds to round weight in metric tons, recreational landings as reported in MRFSS (all modes) from 2000 to 2003, and CRFS (all modes), 2004–08.

TABLE 11

Catch Estimates (metric tons) for common thresher shark (*Alopias vulpinus*) harvested by commercial and recreational fisheries for the period 2000–08 compared to the current 340 mt harvest guideline (HG).

	Commercial DGN* (all sizes)		Commercial Hook & Line		Recreational (all modes)		Commercial, Other Gears **		Total	
Year	Tons	%HG*	Tons	%HG	Tons	%HG	Tons	%HG	Tons	%HG
2000	155.5	45.7	9.0	2.6	13.6	4.0	86.5	25.4	264.5	77.8
2001	272.8	80.2	12.7	3.7	20.6	6.1	74.1	21.8	380.2	111.8
2002	216.2	63.6	5.4	1.6	3.2	0.9	79.1	23.3	303.9	89.4
2003	241.3	71.0	3.8	1.1	27.4	8.1	55.5	16.3	328.0	96.5
2004	67.4	19.8	4.3	1.3	3.3	1.0	43.0	12.7	118.1	34.7
2005	155.1	45.6	1.1	0.3	11.6	3.4	22.0	6.5	189.8	55.8
2006	98.3	28.9	7.4	2.2	22.7	6.7	53.5	15.7	182.0	53.5
2007	166.8	49.1	8.8	2.6	51.8	15.2	27.9	8.2	255.2	75.1
2008	106.9	31.4	9.2	2.7	35.6	10.5	30.9	9.1	182.6	53.7
Avg. 2000-2008	164.5	48.4	6.9	2.0	21.1	6.2	52.5	15.4	244.9	72.0

*- Drift Gill Net (DGN) all mesh sizes ranging from large mesh (>=14 in to small mesh (>3½ in and <14 in

** Other comercial gears include mainly set gillnet and harpoon

CFIS, converted from pounds to round weight in mt; Recreational estimates from RecFIN, MRFSS (2002–03) and CFRS (2004–08)

ulation was recovering. The most recent assessment of thresher shark in 2002 indicated that thresher shark is no longer overfished and recent average landings are about 75% of MSY. However the Council has recommended that a new stock assessment be a priority.

In 2008, the Council evaluated the need to limit the sport take of common thresher sharks. Recreational catch had been increasing, due to the sportfishing public becoming more educated on how to target them, and increasing use of internet websites to disseminate information on fishing areas and thresher shark occurrence. Concerns were raised that the HG might be exceeded and the majority of this catch was occurring during the spring thresher shark pupping season, and many of the fish caught appeared to be pregnant females. Additionally, although many thresher shark anglers advocate catch and release fishing methods, a preliminary study indicated that thresher sharks caught by foul hooking the tail had poor survival rates when released. On further examination of the recent CRFS data, estimates of recreational thresher shark catches were found not to be causing cumulative landings to exceed the HG (fig. 15, tab. 11). Further, an analysis of bag limits showed that few anglers caught limits and a change in the bag limit would

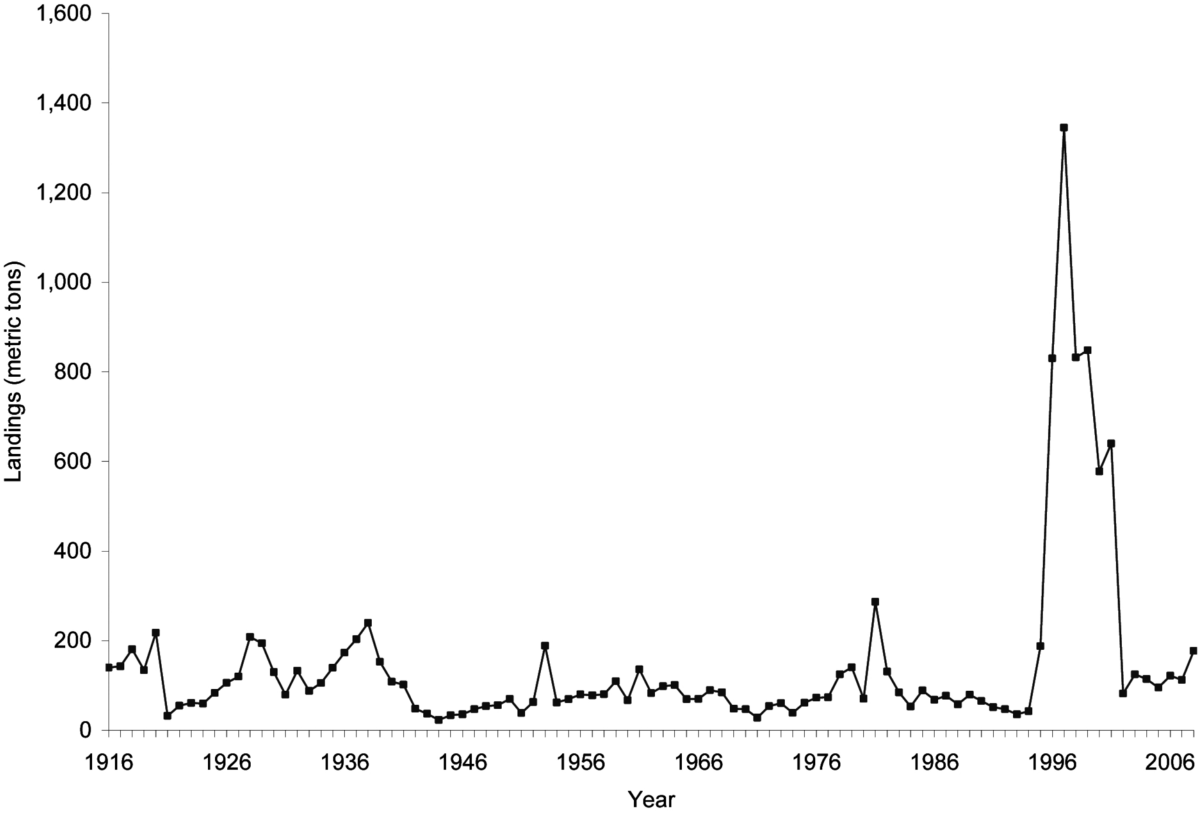

Figure 16. California commercial skate (Rajiformes) landings, 1916–2008.

likely have little effect on recreational catch. The Council decided not to make changes to thresher shark regulations for the 2009–10 management cycle, but did make a number of recommendations including to: (1) continue outreach to fishermen regarding best practices to increase survival of released animals, (2) improve data collection on thresher sharks (especially for private access marinas, and in commercial hook-and-line and non-HMS fisheries), (3) initiate a new stock assessment, incorporating data from Mexico, (4) better estimate the number and condition of released fish, (5) further investigate recreational gear modifications to increase survival, and (6) better identify thresher shark nursery areas.

Skates and Rays

Skates and rays (Rajiformes) have not historically been targeted in commercial fisheries, but have primarily been taken as incidental catch by trawlers in northern and central California. Of those identified in commercial catch, the most common skates are the big skate (*Raja binoculata*), California skate (*Raja inornata*), and longnose skate (*Raja rhina*). The most commonly identified rays are the shovelnose guitarfish (*Rhinobatos productus*) and bat ray (*Myliobatis californica*). This does not reflect actual species composition, however, because the majority of landings have been reported as "unspecified skate" or "stingray". Landings are also reported under specific market categories for those species above (longnose skate just added this year), as well as "unspecified ray", "Pacific electric ray" (*Torpedo californica*), and "thornback" (*Platyrhinoidis triseriata*). Of the 22 species of skates and rays currently known to be in California waters, only the big skates, California skates, and longnose skates are under management authority of the Council Groundfish FMP. Though these species are defined as groundfish, harvest of skates is not actively managed under the Groundfish FMP. The 11 species of rays found in California are not federally managed.

Skates. From 1916 to 1990, California commercial skate landings ranged from a low of 23 t in 1944 to a high of 286 t in 1981, averaging 95 t annually during that period (fig. 16). In the mid 1990s, skate landings increased significantly from about 42 t in 1994 to 1,345 t in 1997 due to increased demand from Asian markets. Landings fell sharply in 2002, corresponding with reduced market demand, and have averaged 118 t annually over the past seven years.

In 2008, commercial landings for skates totaled 177 t, the highest landings since 2001. Landings increased by 58% from the 112 t landed in 2007. Trawl gear accounted for most (94%) of the landings in 2008; longline, gill net, and seine gear accounted for the remaining amount (6%).

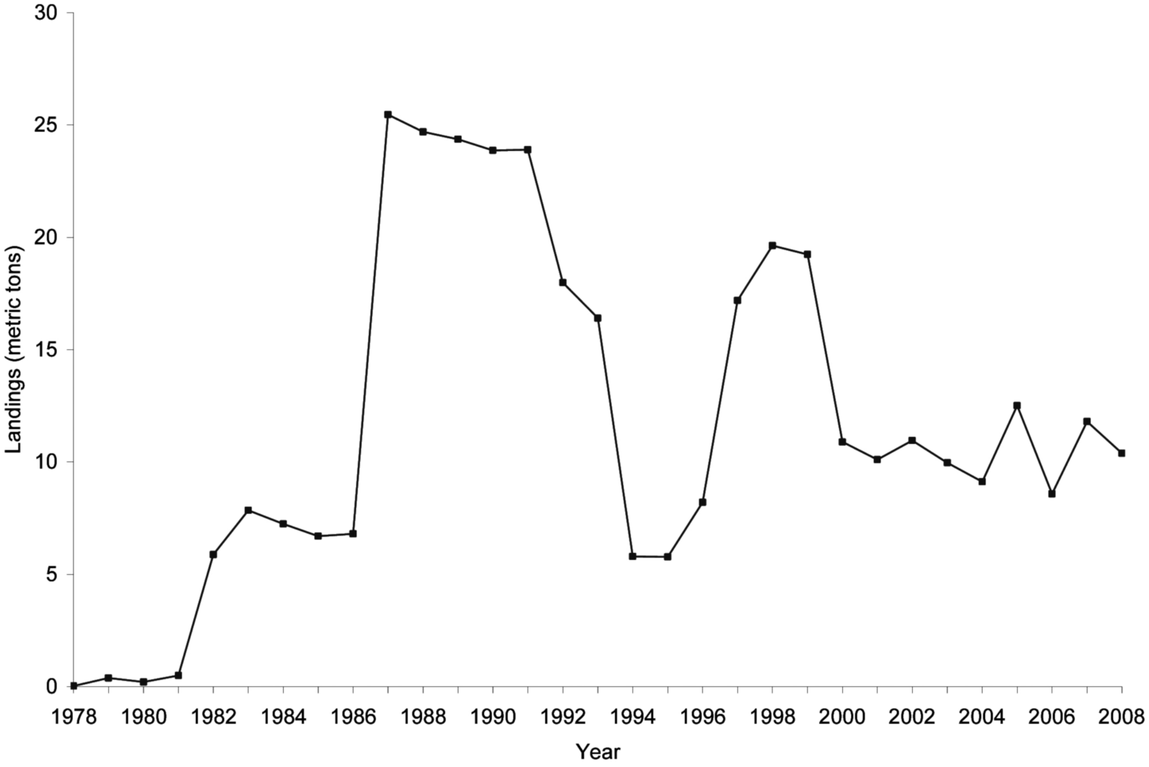

Figure 17. California commercial ray (Rajiformes) landings, 1978–2008.

Over 99% of the skates were landed as "unspecified skate"; the remaining fraction was landed in big skate and California skate market categories.

The ex-vessel economic value for skates during 2008 was $96,958, 89% higher than in 2007 ($51,292), but considerably lower than the peak value reached in 1997 ($510,994). The average ex-vessel price in 2008 was $0.83/kg ($0.40/lb). Historically, the statewide economic value of skate fisheries has been small compared to other fisheries. The average annual ex-vessel price for skates ranged from $0.02/kg ($0.01/lb) in the late 1950s to $0.60/kg ($0.27/lb) in the 1990s. From 2000 to 2008, prices averaged $0.73/kg ($0.33/lb) and reached as high as $22/kg ($10/lb).

The majority of skate landings in 2008 were made in northern California, with Crescent City, Eureka, and Fort Bragg port areas accounting for 90% of the catch. In the earlier years of the fishery, most of the skate catch came through central California (Monterey and San Francisco), which accounted for 41% to 100% of the annual landings from 1948 through 1989 (72% average). Since 1975, the northern California areas have become progressively more important for skate landings. In 1995, the catch from northern California increased dramatically, and has since accounted for 72% to 93% of the total catch. Total landings from areas south of Monterey have continued to be relatively insignificant.

The increase in skate landings may be attributed to retention of previously discarded catch. When the commercial groundfish fishery was divided into limited entry and open access components in 1994, new quotas and regulations were required. The significant reduction of groundfish quotas for both components created more space in boats' holds to retain non-quota species. Trawl vessels were able to supplement groundfish landings with skate and ray bycatch. It is uncertain whether the effort to target the skate and ray resource has increased or if previously discarded catch is simply being retained and landed.

New recommendations were made for the skate fishery in 2009. As a result of the longnose skate stock assessment completed in 2008, catch of this species is now required to be sorted upon landing (Title 14, CCR, § 189(b)(3)). Previously, market categories were limited to only big skates and California skates, though these and other species were mostly lumped into "unspecified skate" in the absence of sorting requirements. Under federal regulations, skates had been part of a species complex because they had not been thoroughly studied nor been assessed. Longnose skate is now removed from the "other species" complex and assigned species-specific allowable biological catch values for the 2009 and 2010 management cycle. State port samplers began sampling the species composition of skate market categories in 2009.

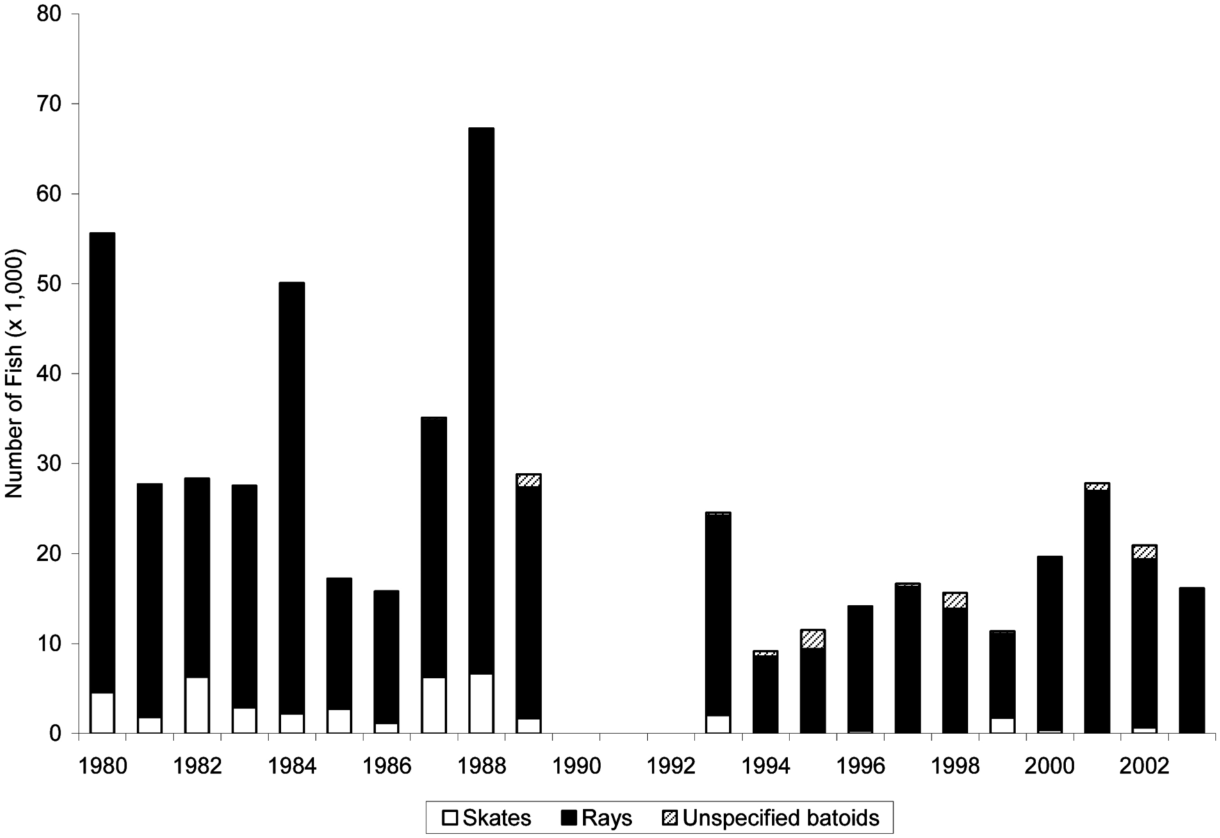

Figure 18. California recreational skate and ray (Rajiformes) landings as reported in the Marine Recreational Fisheries Statistical Survey (MRFSS), 1980–2003.

Current regulations also require all skates to be landed whole (FGC §5508, 8042). The possession of skate wings aboard a vessel is prohibited as there are no equivalents nor conversion factors established in statute or regulation under which not-whole skates may be brought ashore. In the past, only a portion of skate (and ray) catch was marketed whole; primarily, just the pectoral fins or "wings" of skates were sold. Skates are currently marketed both whole and as wings. Wings are sold largely in Asian markets as fresh or fresh-frozen, dried, or dehydrated and salted.

Rays. Commercial landings of rays have been relatively minor compared to skates. However, rays may have been included with skate landings prior to 1978 when commercial landings data became available for rays. Over the past 31 years, ray landings ranged from less than 1 t in 1978 to 25.5 t in 1987, averaging 11.7 t annually (fig. 17). In 2008, reported landings of rays totaled 10.4 t, a 12% decrease from 2007 (11.8 t). Bat rays (38%) and shovelnose guitarfish (33%) accounted for the majority of the landings in 2008. Ray landings have primarily been reported as shovelnose guitarfish, averaging 73% of the landings annually since 1978. The relative proportion of shovelnose guitarfish has been declining since 2006, when this species accounted for 65% of the landings.

The ex-vessel value of rays was $11,962 in 2008, a 16% decrease from 2007 ($14,198). The price of rays has fluctuated considerably compared to skates. The average price rose from $0.15/kg ($0.07/lb) to $4.01/kg ($1.82/lb) from the 1970s to 1980s, and then dropped to $1.63/kg ($0.74/lb) in the 1990s. Between 2000 and 2008, the average price was $1.50 kg ($0.68/lb) with a maximum of $110/kg ($50/lb). In 2008, the average ex-vessel price was $0.87/kg ($0.39/lb), a 37% decrease from 2007 ($1.39/kg; $0.62/lb). Over 99% of the rays were landed in the southern California region in 2008, with the Los Angeles port complex accounting for 77% of the landings.

Recreational fishery. The recreational fishery for skates and rays is relatively small. In 2008, only 3% (7 t) of the estimated 195 t of skates and rays landed in California was recreational and 97% (188 t) was commercial. Small sport fisheries target a few of the shallow nearshore species. Rays dominate the catch (figs. 18, 19); the most common species are bat rays, shovelnose guitarfish, and thornbacks (Raja clavata). In 2008, an estimated 14,900 skates and rays were taken. Catch estimates

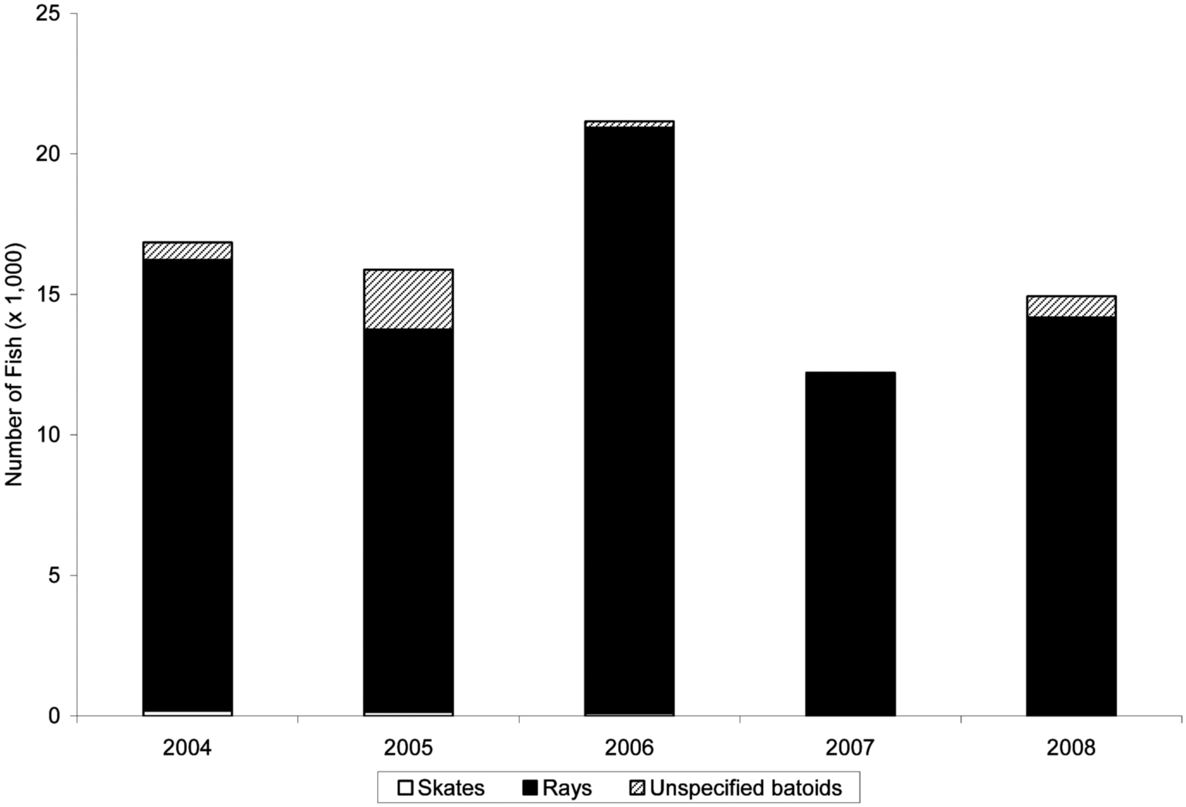

Figure 19. California recreational skate and ray (Rajiformes) landings as reported in the California Recreational Fisheries Survey (CRFS), 2004–2008.

(CRFS) indicate that an average of 16,200 fish (49 t) were taken per year from 2004 to 2008. During this period, rays composed 95% of the catch.

Kellet's Whelk

Statewide commercial landings for Kellet's whelk (*Kelletia kelletii*) in 2008 totaled 73 t, a 6% decrease from the 78 t landed in 2007, and a 16% decrease from the highest yearly recorded landings in 2006 of 87 t. Kellet's whelk landings increased steadily between 1993 and 2006 when they rose from 2 t to 87 t (fig. 20). The ex-vessel value from the 2008 commercial harvest of Kellet's whelks was approximately $132,000, a 3% decrease from the previous high value of approximately $136,000 in 2007. The 2008 ex-vessel price ranged from $0.55 to $6.61/kg with an average of $1.84/kg, up 9% from the 2007 average of $1.69/kg. Since 1979, the fishery's ex-vessel value has ranged from $94 in 1988 to approximately $136,000 in 2007 and the ex-vessel price has ranged from $0.53/kg in 1981 to $1.94/kg in 1992. Prior to 1979, landings were not recorded specifically for Kellet's whelks but minor landings may have occurred and been recorded as miscellaneous mollusks or sea snails.

Landings occurred at 13 ports in 2008 with five ports accounting for 85% of the catch. In 2007, landings occurred at 15 ports with three ports landing 80% of the total catch. Kellet's whelk landings have been reported at 24 ports from 1979 to 2008, with 80% of landings occurring at four ports. The majority of landings in this time period occurred at Santa Barbara (199 t), with approximately 40% of the total landings reported. The other three top ports were Terminal Island, San Diego, and San Pedro, with cumulative landings of 80 t, 69 t and 62 t, respectively.

In 2008, 98% of all harvested Kellet's whelks were taken incidentally in lobster or rock crab traps, compared to the 93% taken in 2007 in the same gear. The remaining take in 2008 occurred through diving or finfish traps, with approximately 1% of the take attributed to each of those gears. Divers harvested 5% of the landings in 2007 and finfish gear harvested the remaining 2%. Since 1979, 89% of all harvested Kellet's whelks have been taken incidentally in lobster and crab traps when they enter to prey on bait and injured crustaceans. Ninety-nine percent of Kellet's whelks are used for human consumption and are mainly sold in domestic live fish markets.

The Kellet's whelk is usually taken incidentally in the lobster and rock crab trap fisheries, both of which are restricted access fisheries. Commercial divers are required

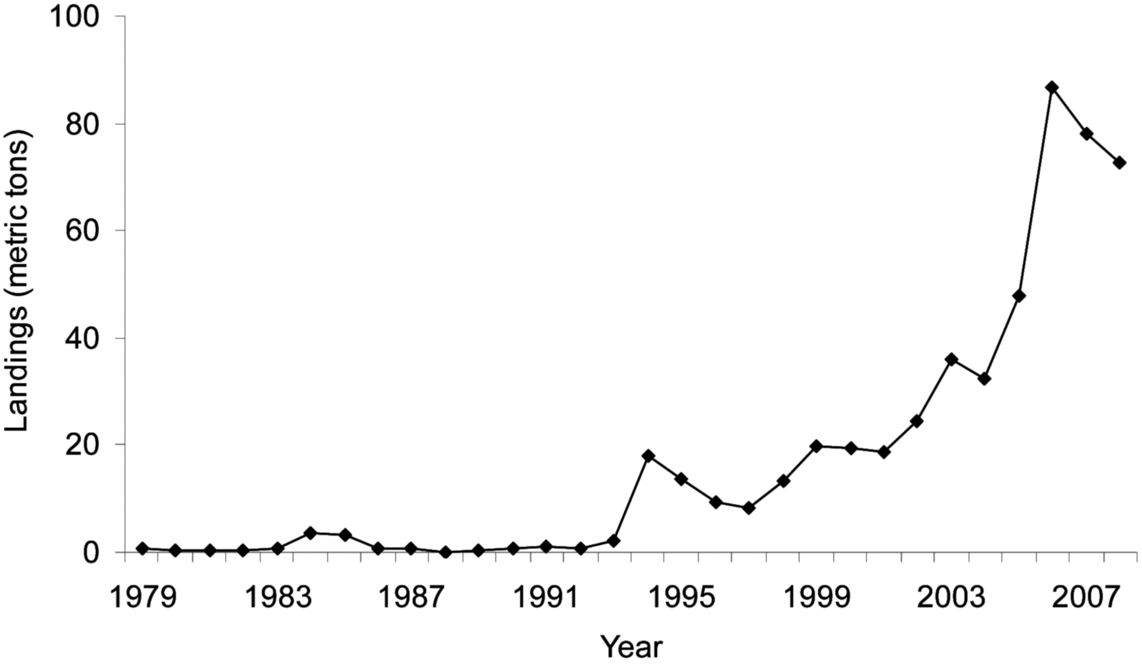

Figure 20. California commercial Kellet's whelk (*Kelletia kelletii*) landings, 1979–08.

to have a commercial license, and may only take whelks further than 1,000 feet (305 m) beyond the low tide mark, as the take of any snails is prohibited in the tidal invertebrate zone. Recreational take of Kellet's whelk by hand is allowed outside of the 1,000 ft (305 m) tidal invertebrate zone. Except where prohibited in state marine reserves, state marine parks and state marine conservation areas the bag limit is 35 animals, with no season.

The Kellet's whelk is a large predatory gastropod commonly found in rocky reefs and kelp bed habitat and ranges from Baja California, Mexico to Monterey, California. Historically the northern boundary of its range extended to Point Conception, California, but in 1980 Kellet's whelk was reported in Monterey, an expansion of over 400 km (248 mi). Studies suggest that the Kellet's whelk range expanded to Monterey Bay in the 1970s or early 1980s, possibly due to an El Niño-Southern Oscillation event, and is dependent on recruits from southern California.

Subject to an expanding fishery, the harvest of Kellet's whelks is not regulated by a minimum size limit, season, or any type of harvest quotas. Kellet's whelks are slow growing snails that aggregate for feeding and spawning, which could make them vulnerable to overfishing. Little is known about the impact of recent increased fishing rates on overall population size or on long-term catch sustainability. The Partnership for Interdisciplinary Studies of Coastal Oceans and Reef Check California currently collect abundance data on the Kellet's whelk during their surveys.

Sea Cucumber

In 2008 a combined total of 370 t of warty sea cucumbers (*Parastichopus parvimensis*) and giant red sea cucumbers (*Parastichopus californicus*) was landed in California (fig. 21). The ex-vessel value of these landings was $1.7 million, an increase of 67% over the 2007 sea cucumber landings (221 t). The average ex-vessel price paid for sea cucumbers in 2008 was $4.65/kg ($2.11/lb), a 53% increase from 2007 ($3.04/kg, $1.37/lb), and ranged from $1.76 to $6.60/kg ($.80 to $3.00/lb).

Warty sea cucumbers are found in the intertidal zone out to a depth of 27 m (14.7 fathoms) and range from Monterey Bay to Baja California. They are uncommon north of Point Conception. Giant red sea cucumbers inhabit the subtidal zone out to 90 m and range from the eastern Gulf of Alaska to Baja California. Both sea cucumber species feed on surface organic nutrients suspended in mud, sand, and detritus. Warty sea cucumbers migrate annually between shallow and deeper water habitats. Trawl fishermen claim that giant red sea cucumbers make similar seasonal migrations up and down their slope habitat, but this has not yet been verified by research.

Warty sea cucumbers are harvested almost exclusively by divers at depths of 4.6 to 24.4 m (2.5 to 13 fathoms), while giant red sea cucumbers are taken by fishing vessels towing bottom trawl gear in 36.6 to 183 m (20 to 100 fathoms) depths. The warty sea cucumber dive fishery occurs primarily in southern California from Santa Barbara County to San Diego County, including the off-

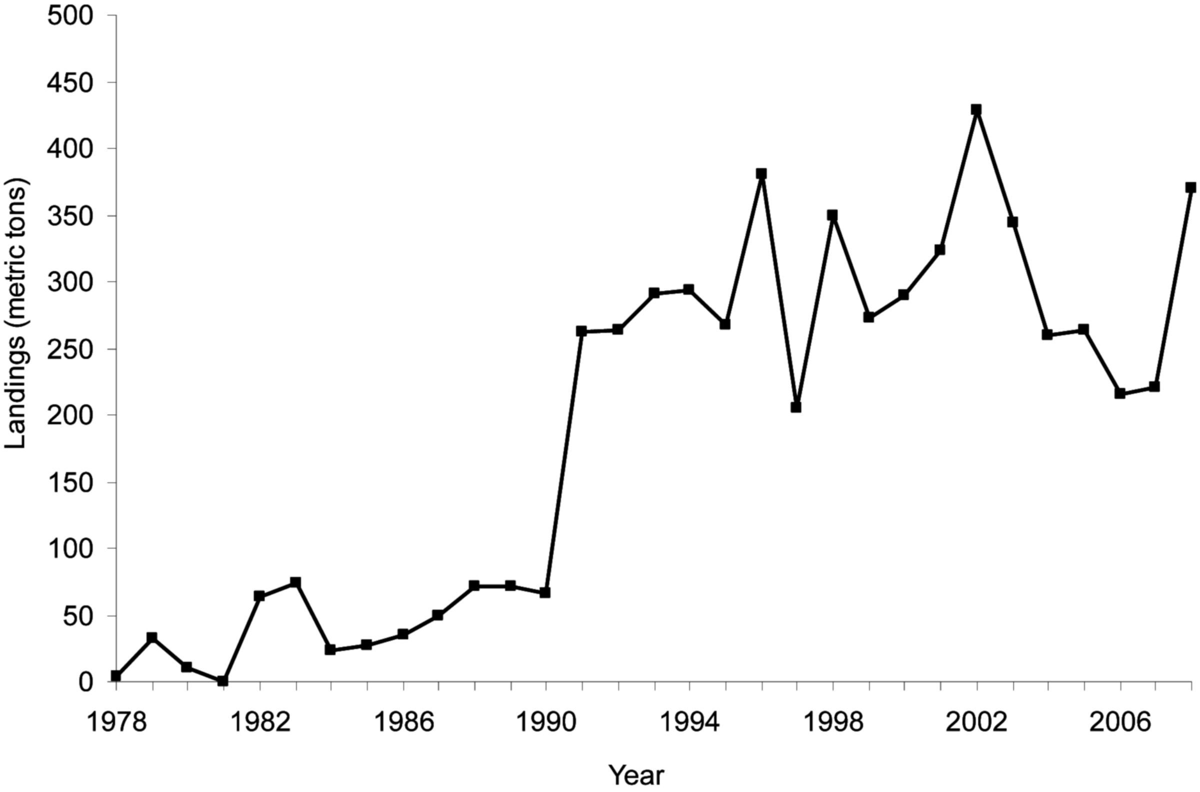

Figure 21. California commercial landings of warty (*Parastichopus parvimensis*) and giant red (*P. californicus*) sea cucumbers, 1978–08.

shore Islands. The giant red sea cucumber trawl fishery occurs in the Southern California Bight with most trawling occurring in the Santa Barbara and the Santa Catalina Channels. Most of the frozen or processed sea cucumber product is shipped overseas to Hong Kong, Taiwan, mainland China, and South Korea. Small quantities are also purchased by Asian markets within the United States. Processed sea cucumbers can sell for a wholesale price of up to $44/kg ($20/lb).

There is no significant sport fishery for sea cucumbers in California; however, recreational take of sea cucumbers is only permitted outside of the tidal invertebrate zone (defined as between the high tide mark and 1,000 ft (305 m) seaward of the low tide mark). Except where prohibited in state marine reserves, state marine parks, and state marine conservation areas, the bag limit is 35 animals, and there are no seasonal closures for sea cucumbers.

Commercial landings of sea cucumbers in California were first recorded in 1978 at Los Angeles County ports. Landings averaged less than 15 t annually until 1982, when the principal fishing area shifted to the Santa Barbara Channel. Landings of sea cucumbers fluctuated from 24 to 73 t over the next eight years, and in 1991 reached more than 262 t. Through the first 18 years of the fishery, trawl landings comprised an average of 75% of the annual sea cucumber harvest, but between 1997 and 2002, divers accounted for up to 88% of the combined sea cucumber landings. During this time period, more than a dozen trawlers were excluded from the fishery for permit violations. At the same time, sea cucumber divers were increasing their harvesting efforts for warty sea cucumbers, due in part to a downturn in the sea urchin fishery, and because the 1997 moratorium on the harvest of abalone had former abalone divers seeking other dive fisheries in which they could participate.

There are no seasonal restrictions, size limits or harvest quotas for the commercial take of sea cucumbers. A restricted access permit was required beginning with the 1992–93 fishing season. The permit was based on meeting a 22.7 kg (50 lb) landing requirement during a four-year (January 1988 to June 1991) window period. In 1997, new legislation imposed additional regulatory measures on the sea cucumber dive and trawl fisheries. The major management changes included the creation of separate permits for the dive and trawl fisheries, and the imposition of a permanent ceiling on the total number of permittees allowed to harvest sea cucumbers (130 divers and 40 trawl fishermen). Additionally, a mechanism allowing for the transfer of sea cucumber permits was included in the new legislation. By 2000 there were 113 sea cucumber dive permittees and 36 sea cucumber trawl permittees. In 2008, the numbers of permitted dive and trawl sea cucumber fishermen had further dropped to 84 and 18, respectively. The decline in numbers was primarily due to retirements and attrition among the older permittees, and by the shift of some dive and trawl fishermen into other, more lucrative, commercial fisheries.

Sea cucumbers exhibit a patchy distribution, a relatively short life span, a low age at maturity, sporadic recruitment, and a high natural mortality. Species with these characteristics typically have a low maximum yield per recruit and are vulnerable to overfishing; however, it is expected that the southern California populations of warty and giant red sea cucumber can sustain current harvest levels, based on the effort-limiting permit restrictions placed on the trawl and dive fisheries.

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THE STATE OF THE CALIFORNIA CURRENT, SPRING 2008–2009: COLD CONDITIONS DRIVE REGIONAL DIFFERENCES IN COASTAL PRODUCTION

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ABSTRACT

This report describes the state of the California Current system (CCS) between the springs of 2008 and 2009 based on observations taken along the west coast of North America. The dominant forcing on the CCS during this time period were La Niña-type conditions that prevailed from the summer of 2007 through early 2009, transitioning to neutral El Niño-Southern Oscillation conditions in the spring of 2009. The Pacific Decadal Oscillation index was negative during this time period and its values had not returned to normal by the spring of 2009. The general effects on the California Current system were stronger than normal southward winds and upwelling as well as generally colder than normal SST and shallow nitraclines; however, there were regional differences. Off Baja California sea surface temperatures did not respond to the La Niña conditions; however, concentrations of chlorophyll *a* (Chl *a*) were significantly above normal, probably due to the anomalously high upwelling off Baja during most of the year. Off southern California there was no clear evidence of increased primary or secondary production, despite observations that previous La Niña conditions affected mixed layer depth, temperatures, nutrients, and nitracline depths. In both central and northern California and Oregon, stronger than normal upwelling increased primary production and prevented potential spawning of sardine north of San Francisco. In central California the midwater fish community resembled that of recent cool years, and cover by kelp was much reduced along the coast. Off Oregon there was evidence of increased abundance of boreal copepods, although the neritic boreal species did not appear to extend as far south as central California. Current predictions are for cooler conditions to change to El Niño conditions by the end of 2009; these are expected to last through the Northern Hemisphere winter of 2009–10.

INTRODUCTION

This report describes the state of the California Current between the springs of 2008 and 2009 based on observations taken along the west coast of North America (fig. 1) by a variety of academic and government observing programs. The North Pacific Ocean has been in a cool phase since the 1998/99 El Niño-Southern Oscillation (ENSO) event, as reflected in values of the Pacific Decadal Oscillation (PDO, fig. 2B) that

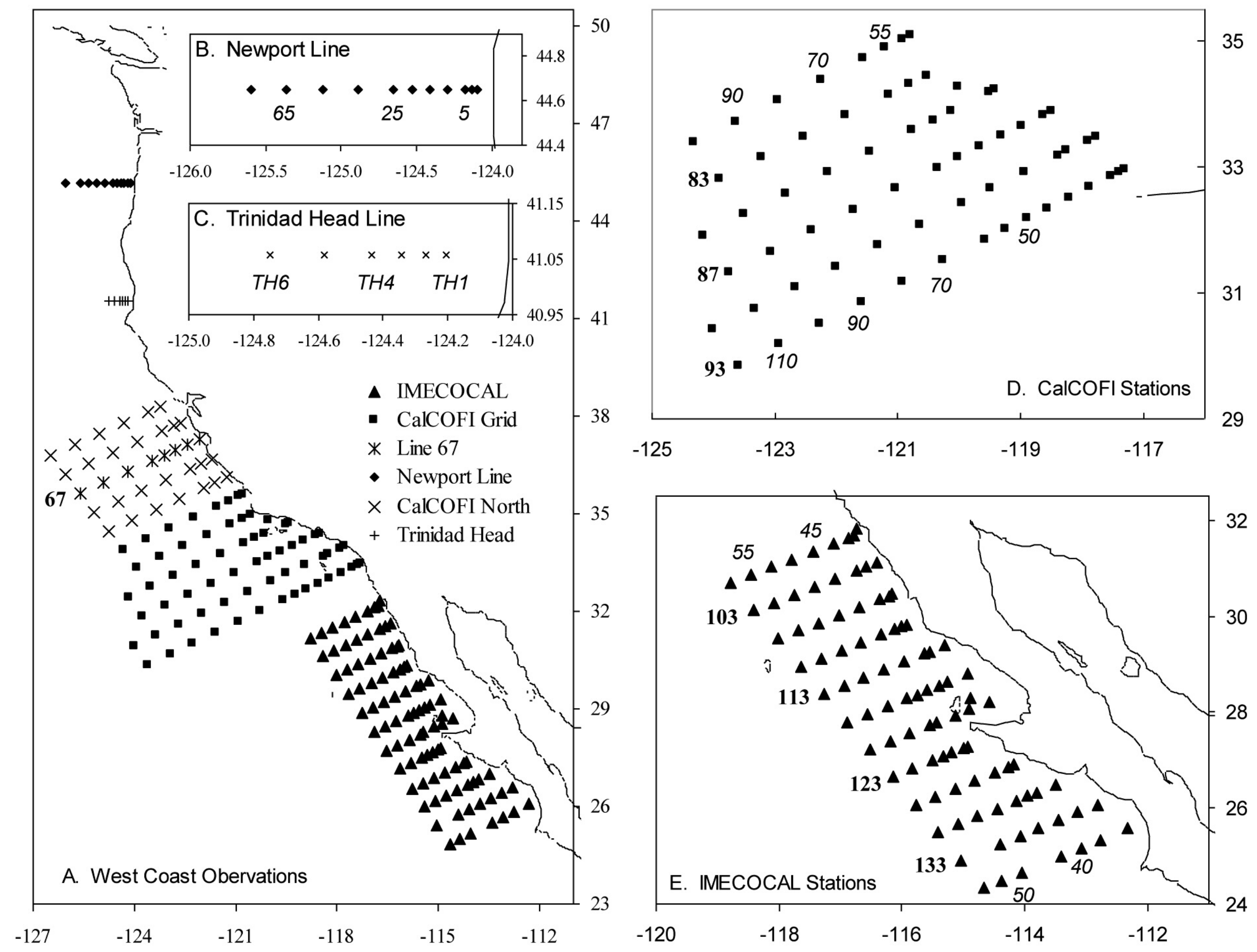

Figure 1. Location of stations where observations were made for this year's report. As appropriate, line numbers are indicated at the end of selected lines; station numbers are indicated above or below selected stations. Line and station numbers for the IMECOCAL and CalCOFI programs follow the CalCOFI line and station nomenclature.

have generally been negative, especially over the last 20 months. Indications of this cool phase are sea surface temperatures (SST) that, since 1999, have been significantly below long-term averages in many regions. At the same time dramatic changes in zooplankton biomass and community structure were observed in some areas (Bograd et al. 2008; Peterson and Schwing, 2003). El Niño events in 2003 and 2006 (fig. 2A) that were relatively weak along the equator, had small or negligible effects on the California Current system (CCS). Variability of biological indices over the last few years has primarily been driven by local- to regional-scale processes. For example the timing and strength of upwelling had very strong effects on local production at all trophic levels during 2005 and 2006 (Peterson et al. 2006; Goericke et al. 2007). In contrast, upwelling during 2007 started early and was anomalously strong, yet most biological indices were similar to their long-term averages (McClatchie et al. 2008).

During 2007, the CCS experienced very strong and persistent La Niña conditions, as reflected in low SST across the domain and upwelling volumes that were slightly above normal. Off southern California nitracline depths were unusually shallow and mixed layer concentrations of nitrate and chlorophyll *a* were unusually high (the latter signal was only evident from satellite data, not from cruise observations). Off Baja California concentrations of chlorophyll *a* were elevated as well, however, SST was normal, with the exception of January 2008. Zooplankton biomass was elevated off Baja and Oregon, but not off southern California, reinforcing the notion that phytoplankton and zooplankton biomass are not tightly coupled off southern California.

The long cool period appears to have had an adverse effect on the sardine population, especially sardine reproductive success, which is thought to respond more quickly to environmental conditions than total biomass or catch of sardine (Wada and Jacobson 1998). Anomalies of sar-

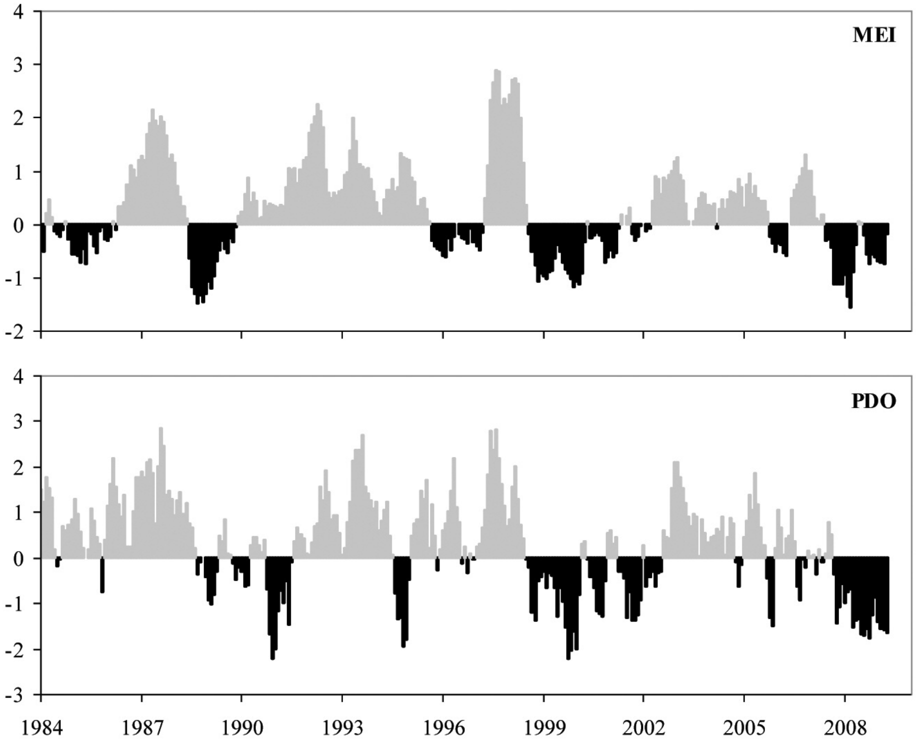

Figure 2. Time series of monthly anomalies of the Multivariate ENSO Index (MEI, http://www.cdc.noaa.gov/people/klaus.wolter/MEI/) and (B) the Pacific Decadal Oscillation (PDO, http://jisao.washington.edu/pdo/PDO.latest), for January 1984–March 2009.

dine reproductive success off California have been strongly negative in seven of the last 10 years (since 1999) (Hill et al. 2008). Based on the NOAA criteria for El Niño/La Niña classification using the Oceanic Niño Index, 1998–2000, 2000–01 and 2007–08 all contained seasonal periods classified as historical La Niñas, whereas 2002–03, 2004–05, and 2006–06/07 had periods classified as historical El Niños. Negative sardine reproductive success coincided with the cool La Niña conditions at the start and end of the decade, whereas the warmer El Niño conditions from 2002 to 2006 were associated with better (approximately average) sardine reproductive success.

Over the last year cold conditions have persisted, as reflected in the Multivariate ENSO (MEI) and PDO indices (fig. 2), resulting in one of the longest such cool periods in recent history. It is the objective of this report to summarize the response of the CCS to these continuing conditions, both from a physical and biological perspective. Basinwide SST anomalies associated with La Niña conditions typically have a horseshoe pattern delineating regions of positive anomalies in the central gyres, a horseshoe pattern of negative anomalies along the coast of the U.S. and Canada and a region of neutral or positive anomalies off Baja California (fig. 3). If local responses to the cool conditions were simply driven by local meteorological forcing, as reflected for example in SST or rates of upwelling, predicting the response of the ecosystem would be easy. However, since local systems are linked to remote systems through the CCS, local conditions are expected to be partially dependent on conditioning of the CCS upstream. Even though a rigorous analysis of these processes is beyond the scope of this report, this is an opportunity to compare the responses of different regions at different trophic levels and attempt to relate these responses qualitatively to either local forcing or remote forcing via the CCS.

DATA SETS AND METHODS

Climatology

Large-scale wind and temperature patterns were 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° x 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) were 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 were plotted against the harmonic mean of each buoy.

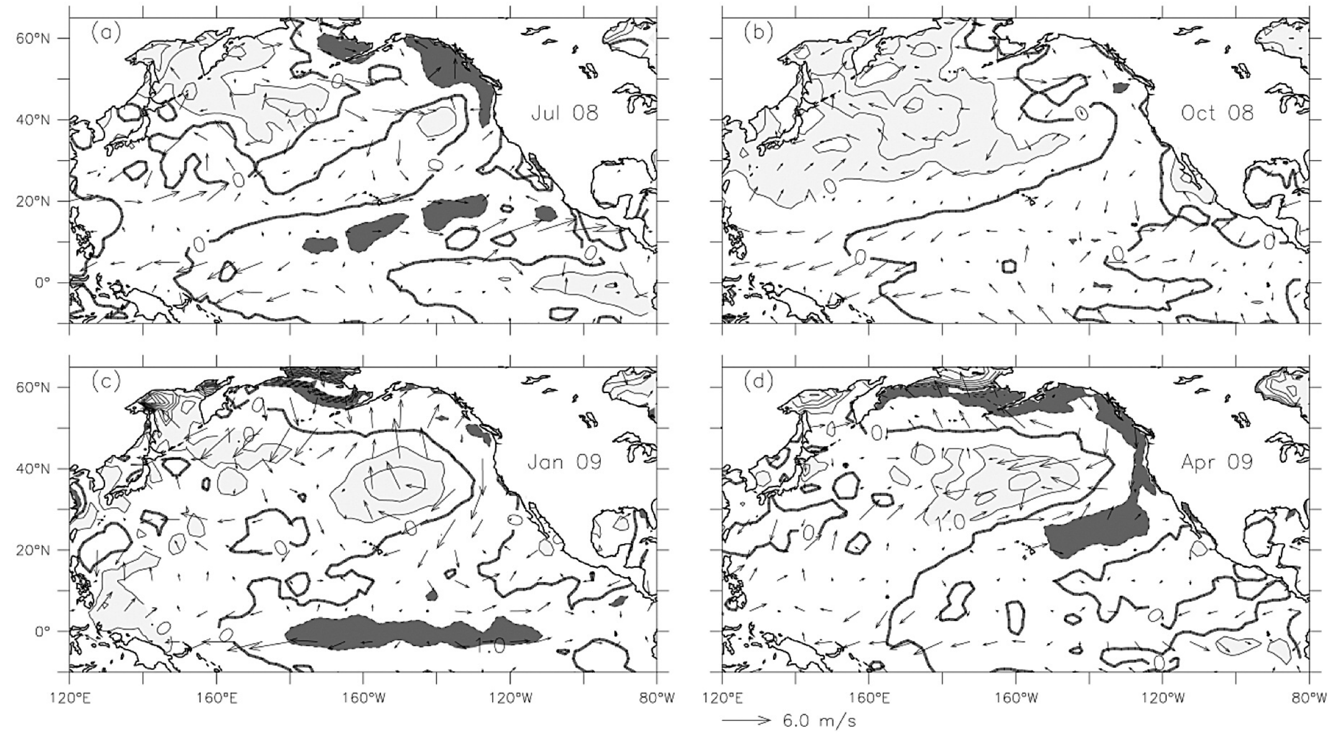

Figure 3. Anomalies of surface wind velocity and sea surface temperature (SST) in the North Pacific Ocean, for (A) July 2008, (B) October 2008, (C) January 2009, and (D) April 2009. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative (cool) SST anomalies less than -1° Celsius are shaded dark grey. Positive (warm) SST anomalies larger than 1° Celsius are shaded light grey. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

Remote Sensing

We used full resolution chlorophyll *a* (Chl *a*) and SST data (http://spg.ucsd.edu/Satellite_data/California_Current/) that were merged from multiple sensors in order to provide the best coverage at 1 km spatial resolution. OCTS (1996–97), SeaWiFS, MODIS-Aqua and MODIS-Terra Level-2 data sets were downloaded from the NASA Ocean Color Processing Group (http://oceancolor.gsfc.nasa.gov/) and AVHRR SST data from the Physical Oceanography DAAC (http://podaac.jpl.nasa.gov/). Corresponding sea surface temperature (SST) data were merged from AVHRR, MODIS-Aqua and MODIS-Terra sensors. A description of the satellite sensors is found in McClain 2009.

Monthly composites from November 1996 to April 2009, corresponding to the period of available high-quality ocean color data were used for both Chl *a* and SST. Monthly means were created at reduced spatial resolution (8 km) by averaging corresponding monthly composites over all years. Anomalies relative to the monthly means were calculated as either the ratio to the monthly mean (Chl *a*) or the difference from the monthly mean (SST). Principal components and respective empirical orthogonal functions (EOF) were calculated using the monthly anomaly data sets.

Time series of satellite-derived Chl *a* or SST were plotted as mean values on a 3 x 4 grid of characteristic areas parallel to the coast with bands of 0–100 km, 100–300 km and 300–1000 km from the coast (Kahru and Mitchell 2001; 2002).

REGIONAL STUDIES

Oregon (Newport Line)

Regular sampling of the Newport Hydrographic (NH) line along 44.65°N (fig. 1) began in 1996 and continues on a biweekly basis along the inner portions of the line, at seven stations, ranging from 1 to 25 nm from shore. The Newport Line station names designate distance (nm) from shore. Occasional cruises sampled further offshore. Methods and measurements are reported in Peterson et al. 2006. Standard hydrographic measurements are made and zooplankton are collected with a 0.5 m diameter, 200 µm mesh net, hauled vertically from a maximum of 100 m to the sea surface. Since 1998, pelagic forage and predatory fish have been sampled from shelf waters biweekly, at night, from mid April through mid July. Four stations are occupied along each of two transects off the Columbia River and southern Washington. At each station, a pelagic rope trawl was towed for 30 minutes between the surface and 20 m. Additional details may be found in previous reports.

Northern California (Trinidad Head Line)

Regular sampling at roughly monthly intervals was carried out along the Trinidad Head Line (six stations along 41°3.50'N, 124°12'N to 124°45'N; fig. 1), subject to constraints imposed by weather and vessel availability. All cruises were conducted aboard Humboldt State University's RV *Coral Sea* except for the March 2008 cruise which was conducted aboard the NOAA RV *Miller Freeman*. All sampling since November 2007, with the exception of cruises in March 2008 and early April 2009, has been conducted at night. Since the fall of 2008 the Newport Line zooplankton protocol has been used on the Trinidad Head transect. Only three stations (TH02, TH03, and TH04) were sampled on 12 April 2009.

Northern and Central California Kelp Surveys

Kelp canopy surface areas are compiled by the California Department of Fish and Game. Data are collected using kelp-fly-over methodology between Pigeon Point and the Oregon border (http://www.dfg.ca.gov/biogeodata/gis/mr_nat_res.asp).

Central California Hydrographic Surveys (Line 67)

A CTD section extending offshore from Monterey Bay to a distance of 315 km (CalCOFI Line 67, fig. 1A) has been sampled on a regular basis since 1997. CTD station spacing is 10 nm and the water column is sampled to a depth of 1000 m. Between spring 2008 and spring 2009, surveys were conducted in June and October 2008 and January 2009.

Central California Coastal Time Series

Data are collected from eight stations in Monterey Bay. Daily means are interpolated to two-week intervals and smoothed with a nine-point running average. The long-term mean is based upon values collected between 1989 and 2008.

Central California Midwater Trawl Survey

The Fisheries Ecology Division (NOAA Fisheries, SWFSC) has conducted a midwater trawl survey annually since 1983 during May–June. Detailed methods are given by Baltz 2008. For this paper, statistics have been summarized from the core area of the survey off central California, extending from 36°30'–38°30'N (Point Piños to Bodega Head). Within this area hydrographic data collected by CTD casts were coarsely stratified by latitude (37° and 38°) and bottom depth (<200m vs. >200m). A variety of epipelagic fish and invertebrate micronekton/nekton are sampled by the midwater trawl, which is fitted with a 1cm mesh cod-end liner. Young-of-the-year (YOY) groundfishes have been counted since 1986, including rockfishes (*Sebastes* spp.), sanddabs (*Citharichthys* spp.), Pacific whiting (*Merluccius productus*), and lingcod (*Ophiodon elongatus*). Likewise, catches of several important coastal pelagic species (northern anchovy [*Engraulis mordax*], Pacific sardine [*Sardinops sagax*], and market squid [*Loligo opalescens*]), as well as deep-scattering layer mesopelagic species (e.g., lanternfishes [Myctophidae], California smoothtongue [*Leuroglossus stilbius*], and sergestid shrimp) have been routinely recorded.

Southern California (CalCOFI)

The CalCOFI program samples 66 stations on a quarterly basis along six lines between Point Conception and the Mexican Border (fig. 1D), weather permitting. During the winter and spring cruises the pattern is extended north for observations of hydrographic properties and distributions of fish eggs and larvae. The water column is routinely profiled to a depth of 500 m, or 10 m off the bottom, using conductivity, temperature, pressure, oxygen, fluorescence, and light transmission sensors. Water samples are retrieved from 12 to 20 depths and salinity, dissolved oxygen, nutrients, and chlorophyll are determined. Standard (0.505 mm mesh) oblique bongo tows are conducted to 210 m depth at each station. The following sampling and analytical protocols are presented in data reports and on the CalCOFI website; both at http://www.calcofi.org.

Results from four cruises off southern California (CC0807, CC0811, CC0901 and CC0903) are presented and compared to the long-term conditions in the study area. Detailed descriptions of the cruises and methods used to collect data and analyze samples are given at http://www.CalCOFI.net. Results from these cruises are presented as time series of cruise averages over all 66 stations (fig. 1C) or as anomalies with respect to the 1984–2008 time series. The mixed layer depth is calculated using a density criterion and set either to 12 m or to the half-way point between the two sampling depths where the σ_θ gradient first reaches values larger than 0.002 per m, whichever is larger. The 12 m cutoff avoids including the daytime thermocline in the analysis. This procedure will introduce a positive bias in calculation of the mixed layer depth but, because the bias is consistent, it will not affect the interpretation of patterns. The nitracline depth is defined as the depth where concentrations of nitrate reach values of 1 µM, calculated from measurements at discrete depths using linear interpolation.

Cetaceans

Two trained marine mammal observers were posted on the flying bridge (0803JD) or bridge wings (0808NH, 0810NH, 0901NH) to scan for cetaceans using binoculars (7-power and 18- or 25-power magnification) and the naked eye. Visual observations were conducted during daylight hours while the ship was underway steaming at approximately 10 kn between stations. Search effort was curtailed in Beaufort sea states of 6 or more and/or in visibility of less than 0.5 nm. Opportunistic sighting data were also recorded while the ship was on station or during inclement weather/sea state.

During daylight transits, we towed a six-element hydrophone array with recording bandwidth of 3 kHz to 96 or 250 kHz, effective for recording primarily odontocete clicks and whistles. At about 1–2 nm distance from each daylight station, we deployed an omnidirectional Navy sonobuoy with effective recording bandwidth of ~5 Hz to 22 kHz for recording baleen whale calls and low-frequency odontocete sounds such as whistles.

NOAA Coast-Wide Surveys

In 2008, two coast-wide surveys (NMFS California Current Ecosystem Survey) were conducted by Fisheries Resources Division (NOAA Fisheries, SWFSC). Both surveys were planned to cover the area from San Diego to the U.S.-Canadian border. Surveys ran from March 24 to May 1 (survey 0804) and from June 30 to August 20 (survey 0807). During the survey, ichthyoplankton samples were taken aboard the NOAA RV *Miller Freeman* (1–30 April, 0804MF) from Cape Flattery, Washington, to San Francisco (48.47°–36.6°N), and aboard the NOAA RV *David Starr Jordan* (24 March–1 May, 0804JD) from San Diego to San Francisco (CalCOFI Line 93.3–62.3). The *Jordan* cruise included the routine CalCOFI cruise (CalCOFI Line 93.3–76.6, 24 March–8 April, fig. 1D). Adaptive sampling of sardine eggs was applied during the coast wide survey but not during the CalCOFI cruise. Survey 0807JD was conducted entirely aboard the *David Starr Jordan* with ichthyoplankton and trawl samples. Hydrographic, acoustic and seabird data were also collected, but are not presented here (see McClatchie 2009)

Baja California (IMECOCAL)

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying 93 stations off Baja California, México (fig. 1E). Station designation follows the traditional CalCOFI nomenclature; thus sampling followed lines 100 to 137. The IMECOCAL program covers all lines out to stations 60, i.e., the westernmost station on any IMECOCAL line is 60. The core oceanographic data set collected at each station includes a conductivity-temperature-depth (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 l Niskin bottles at 0, 10, 20, 50, 100, 150, and 200 m depths to determine dissolved oxygen, Chl *a* , nutrients (NO3, NO2, PO4, SiO3), and primary production. Macrozooplankton is sampled with bongo net tows from 200 m to the surface. IMECOCAL cruise schedules, data collection, methods, and analysis are fully described at http://imecocal.cicese.mx.

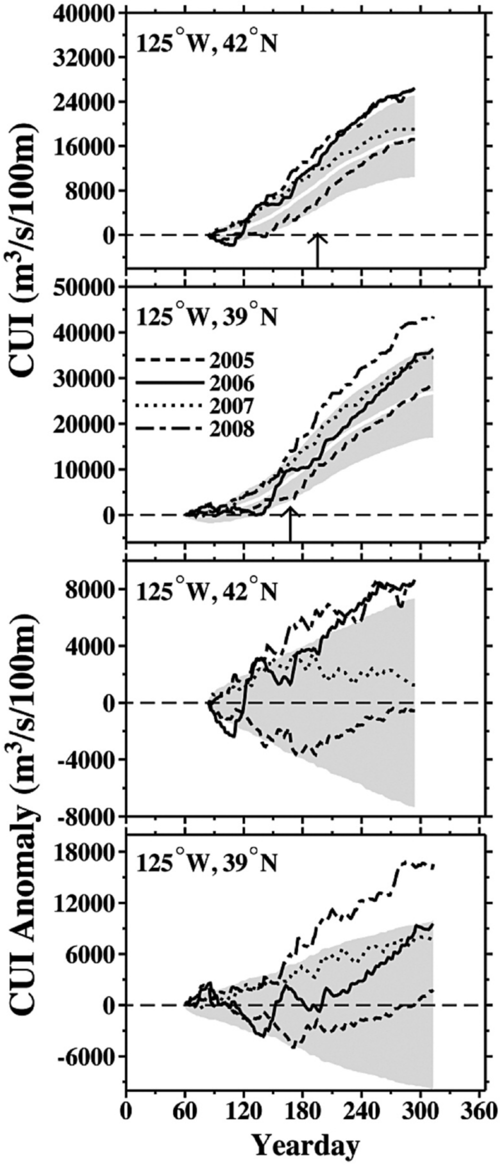

Figure 4. Cumulative upwelling index (CUI; m^3/s/100 km; upper two panels) and CUI anomalies (m^3/s/100 km; lower two panels) for two locations in the California Current. Integration was performed over the climatological upwelling season at each latitude, and arrows mark the time of maximum climatological upwelling at each latitude. Mean and standard deviation (white solid and shaded areas, respectively), and 2005, 2006, 2007, and 2008 are shown.

Anomalies used in this report were calculated by removing the seasonal means of the period 1997–2008.

RESULTS

Large-Scale Patterns

Climatology: La Niña conditions prevailed in the tropical Pacific from summer 2007 through early 2009,

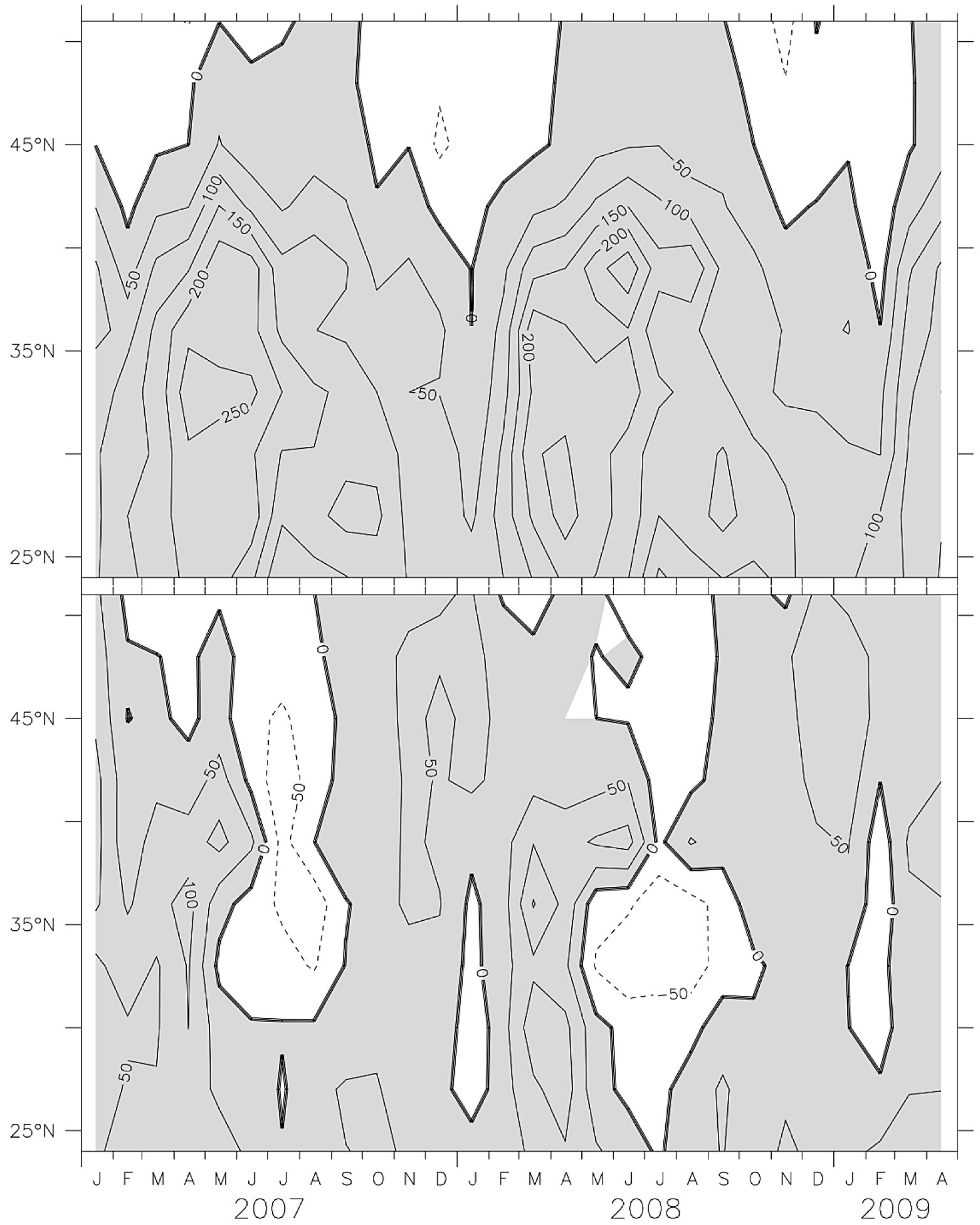

Figure 5. Monthly upwelling index (top) and upwelling index anomaly (bottom) for January 2007–April 2009. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m³/s per 100 km of coastline.

with SST anomalies in the Niño3.4 region (5°N to 5°S, from 170°W to 120°W) exceeding −1°C from October 2007 through February 2008 (fig. 3). The 2007–08 La Niña event was the strongest since 2000 (http://www.cdc.noaa.gov/people/klaus.wolter/MEI/). Near-neutral conditions returned in summer 2008, followed by cooling and the re-development of a weak La Niña. By April 2009, negative SST anomalies had weakened and positive SST anomalies had strengthened in the equatorial Pacific, thus ending the 2008–09 La Niña, transitioning briefly to ENSO-neutral conditions and by June to El Niño conditions (NOAA CPC Climate Diagnostics Bulletin) (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.shtml).

In the extra-tropical North Pacific Ocean, SST anomalies displayed the typical horseshoe pattern of La Niña through the latter half of 2008 and continuing into early 2009 (fig. 3). This pattern also reflects the negative phase of the PDO, which has persisted since autumn 2007 (fig. 2). Negative SST anomalies on the order of −1°C

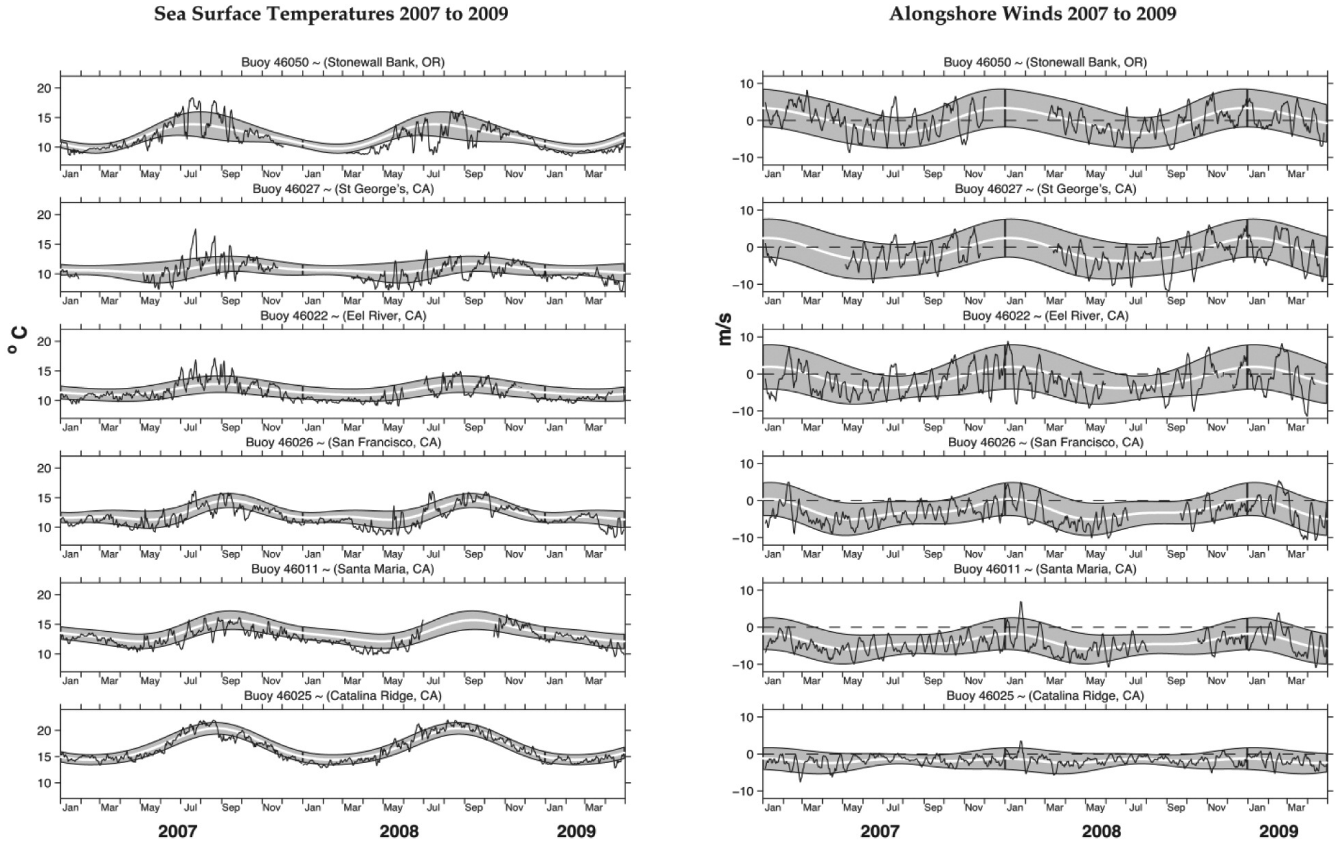

Figure 6. Time series of daily-averaged SST (left) and alongshore winds (right) for January 2007–February 2009 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a seven-day running mean. Data provided by NOAA NDBC. Coordinates for buoy locations are at http://www.ndbc.noaa.gov/to_station.shtml.

extended throughout the California Current and Gulf of Alaska through winter 2008–09 and into spring 2009, and wrapped in a horseshoe shape around a broad region of positive SST anomalies (up to +2°C) in the central North Pacific Ocean (fig. 3). Month-to-month SST anomaly changes in the North Pacific Ocean have been controlled locally by a combination of air-sea heat fluxes and Ekman transport and pumping (open ocean upwelling).

The effect of this large-scale pattern on the California Current has been anomalously strong southward coastal winds, stronger than normal upwelling along the West Coast (figs. 4 and 5) and reduced SST. With the exception of a brief period of weaker than normal upwelling in the summers of 2007 and 2008, West Coast upwelling index anomalies have been positive since late summer 2006. Wind anomaly patterns in early 2009 reflect anomalously strong high pressure over the northeast Pacific (fig. 3C, D) and very high upwelling (figs. 4 and 5).

Conditions at coastal NDBC buoys have reflected these large-scale patterns. Buoy winds have been generally upwelling-favorable (southward), with a number of very strong upwelling episodes (e.g., March 2009 at Eel River; fig. 6). This has included several strong upwelling episodes in autumn 2008 and winter 2009, which could lead to a pre-conditioning of the California Current toward a more productive state (Schroeder et al. 2009). A strong cycle of upwelling/downwelling events has been evident since 2007, and may be linked to an active period of the intraseasonal Madden-Julian Oscillation, which is characterized by 30–60 day variability in the tropics. Buoy SSTs were near-normal in 2008 but have become anomalously cool in 2009.

Satellite remote sensing: Trends and patterns in the time series of satellite-derived chlorophyll *a* concentrations and SST in the California Current were analyzed for the period of 1996–2009. Near-shore areas (within 100 km from the coast) in central and southern California showed a trend of increasing Chl *a*. SST was colder than normal over most of the area in the first half of 2008 but turned warmer than normal along the coast of Baja California in the second half of 2008.

We used the first EOFs of Chl *a* and SST as an indicator of the dominant variability pattern. For Chl *a*, the main features of variability were associated with the intensity of upwelling off Point Conception, off the coasts

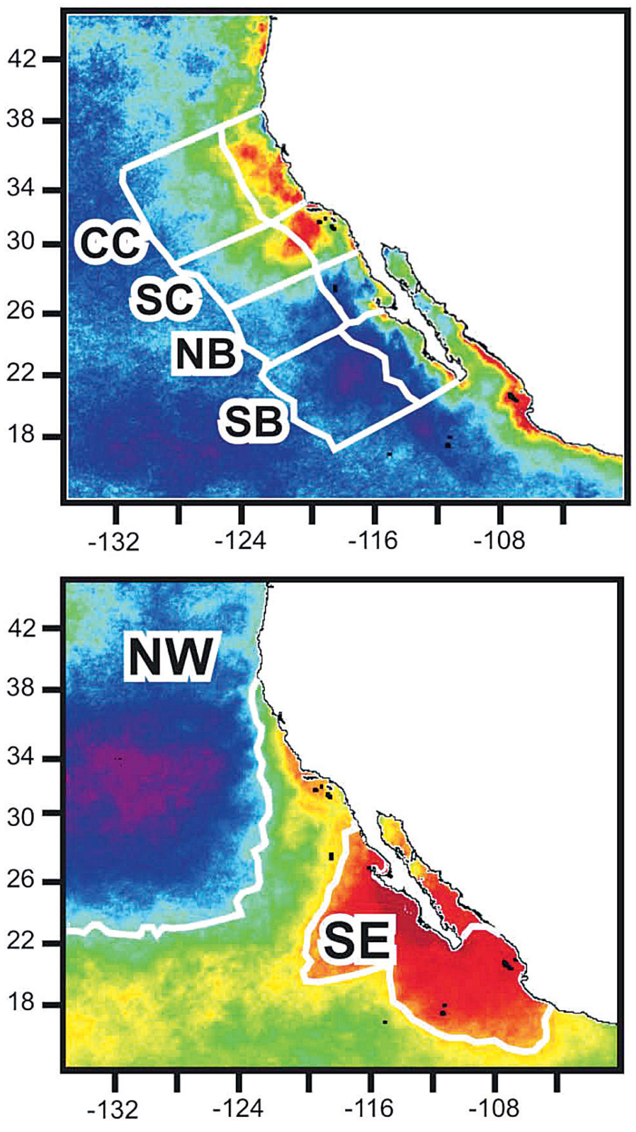

Figure 7. (top) First EOF of the distribution of Chl *a* using monthly anomalies from November 1997 to April 2009. The white lines parallel to the coast are 1000 and 300 km from the coast. (bottom) First EOF of the distribution of SST using the monthly anomalies. The white contours show the main domains of the variability pattern for SST (NW and SE).

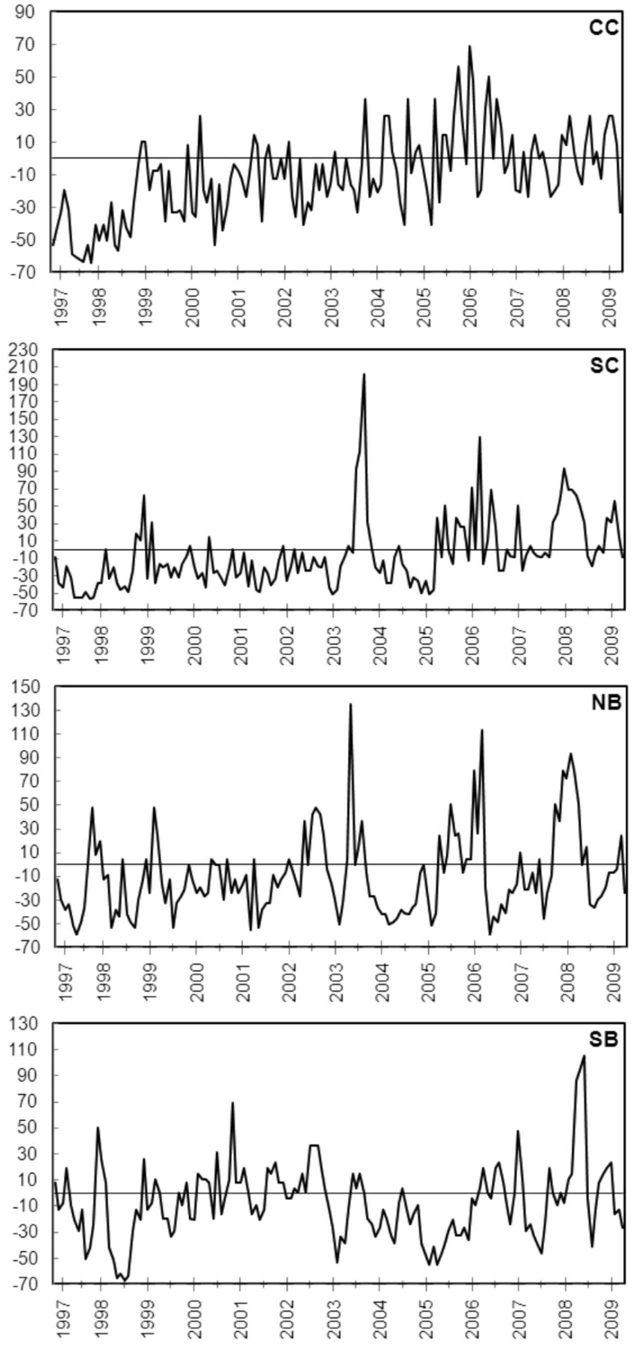

Figure 8. Monthly anomalies of Chl *a* concentration (%) in the 100 km wide band along the coast in central California (CC), southern California (SC), northern Baja California (NB) and southern Baja California (SB). Long-term means are the horizontal lines.

of central California and Oregon and off the Mexican mainland (fig. 7A). For SST the main pattern was a dipole-like structure between the north-west and south-east (fig. 7B). Chl *a* distribution had a much more complex variability structure than the SST distribution as the first EOF explained only 5.8% of the total variance in Chl *a* compared to 15.4% of the total variance in SST.

Time series of Chl *a* concentrations within the 100 km wide coastal zone showed some contrasting patterns. A significant trend of increasing Chl *a* was detected off central California (fig. 8, CC). The increasing phytoplankton bloom magnitude was reported earlier (Kahru and Mitchell 2008; Kahru et al. 2009). The more variable but still significant increasing trend off southern California (fig. 8, SC) was interrupted by periods of strong positive anomalies (+200% anomaly in the summer of 2003, +90% anomaly in the winter of 2007/08) and negative anomalies (winter of 2004/05). Strong interannual variability without a significant trend was evident off the northern and southern Baja domains (fig. 8, NB

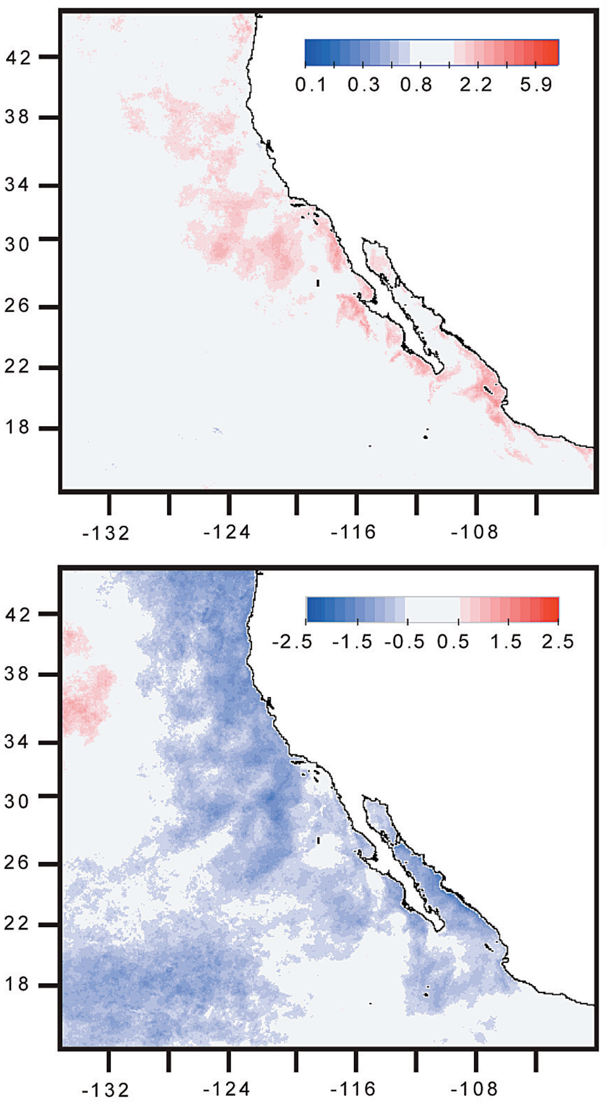

Figure 9. Means of the January 2008 to June 2008 monthly anomalies for Chl *a* (top) and SST (bottom) showing the dominance of areas with higher than normal Chl a and colder than normal SST. The anomaly for Chl a is expressed as a ratio of the actual values to the long-term mean value. The anomaly for SST is expressed as the deviation from the long-term monthly value.

and SB). From the spring of 2008 to the spring of 2009, Chl *a* was generally slightly above the long-term mean in the central and southern California domains but fluctuated strongly in the two Baja domains. The first half of 2008 showed higher than normal Chl *a* and colder than normal SST over large areas (fig. 9).

Regional Studies

Oregon: Sea surface temperatures at the Stonewall Bank NOAA Buoy located 22 miles off Newport were highly variable during the summer of 2008 (fig. 6). The sea surface temperature anomaly for May–September 2008 at the Newport mid-shelf station, NH 05, was −0.81°C. Off Newport, upwelling timing and volume were close to long-term averages during the summer of 2008 (fig. 5, 44.7°N). Averaged over the year, upwelling volumes were slightly above average. In contrast to previous years when most summer cruises showed some degree of hypoxia, oxygen concentrations at 50 m at our mid-shelf station (NH 05) only fell below the hypoxic level of 1.4 mL/L on two cruises out of 15 cruises carried out in May through September. Early summer (April–June) surface nitrate concentrations (8.0 µM) were above the long-term average (5.1 ± 2.7 µM); July–August concentrations were similar to long-term average, 13.1 vs. 10.0 ± 2.8 µM. Concentrations of Chl *a* were similar to long-term averages during the early summer and slightly below long-term averages during July and August.

The years 2007–09 were characterized by conspicuously high abundances of the boreal oceanic copepods *Neocalanus plumchrus* and *N. cristatus* off the coasts of Oregon and northern California. Although the reasons for this are not yet clear, this observation does suggest a greater influence of sub-arctic waters on the northern California Current, beginning in February/March 2007. The time series of copepod biomass and species composition collected at the baseline station NH 05 off Newport showed a resurgence of "northern copepods" beginning in 2006, and continuing through 2007–09 (fig. 10A). The May–September average values of northern copepod biomass and the PDO generally covary (fig. 10B).

Comparison of Newport, Oregon line with Trinidad Head, California line: The samples collected at Trinidad Head station TH02 have been analyzed to compare zooplankton community structure along the Trinidad and Newport lines. TH02 was selected for the initial analysis because it was in the same water depth (~ 70 m) as the most frequently sampled station on the Newport line, NH 05, in 62 m of water. Along the Trinidad Head transect 2008-shelf waters were colder than in 2007. Initial results show that despite the two stations being in inner-to-midshelf waters, TH02 is quite different from station NH 05 in two ways: first, TH02 had a more oceanic zooplankton assemblage including the boreal oceanic species *Neocalanus plumchrus, N. cristatus, Microcalanus pusillus*, and the warm-water oceanic copepod *Calanus pacificus*, second, TH02 had much lower abundances of the boreal neritic copepod species that are common off central Oregon: *Calanus marshallae, Tortanus discaudatus* and *Centropages abdominanlis*.

Planktivorous and Predatory Pelagic Fish Surveys

Results of the bi-weekly pelagic fish surveys in 2008 have not yet shown that small planktivorous pelagic fish have had the expected positive response to the change to cold ocean conditions that began in September 2007 (fig. 11). We hypothesize that the populations of adult anchovy, herring, and white bait smelt were reduced to

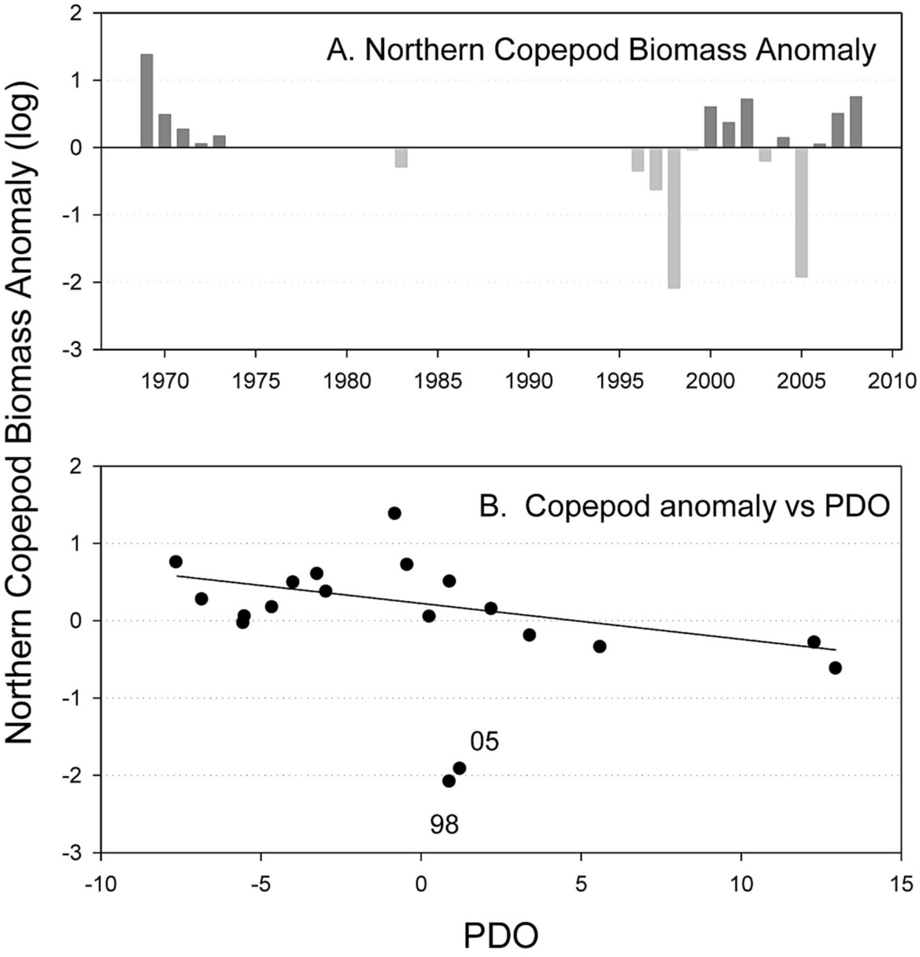

Figure 10. (A) Biomass anomalies of northern copepods (*Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis*) at a mid-shelf station (NH 05) off Newport, Oregon-averaged over the months May–September, showing both historical data (1969–73, 1983) and data from the more recent time series (1996–present). (B) correlation of the northern copepod biomass with the PDO, both averaged over May–September [$y = 0.224x - 0.046$; $R^2 = 0.34$, $p = 0.015$]. Note the similarity between biomass anomalies in 1998 and 2005.

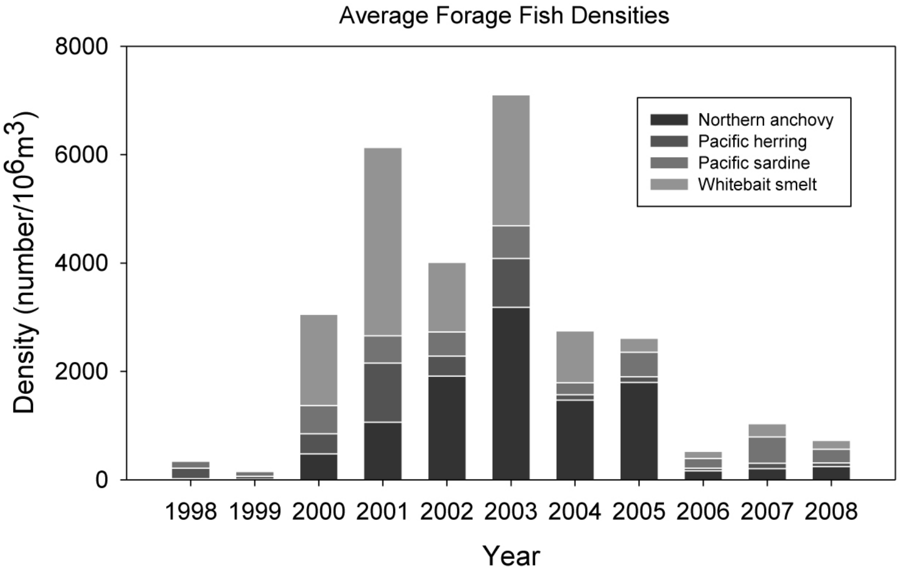

Figure 11. Catches of small pelagic fishes sampled off the Columbia River and Willapa Bay, Washington, with a pelagic rope trawl, at night. Data are averaged over the biweekly May–August cruises.

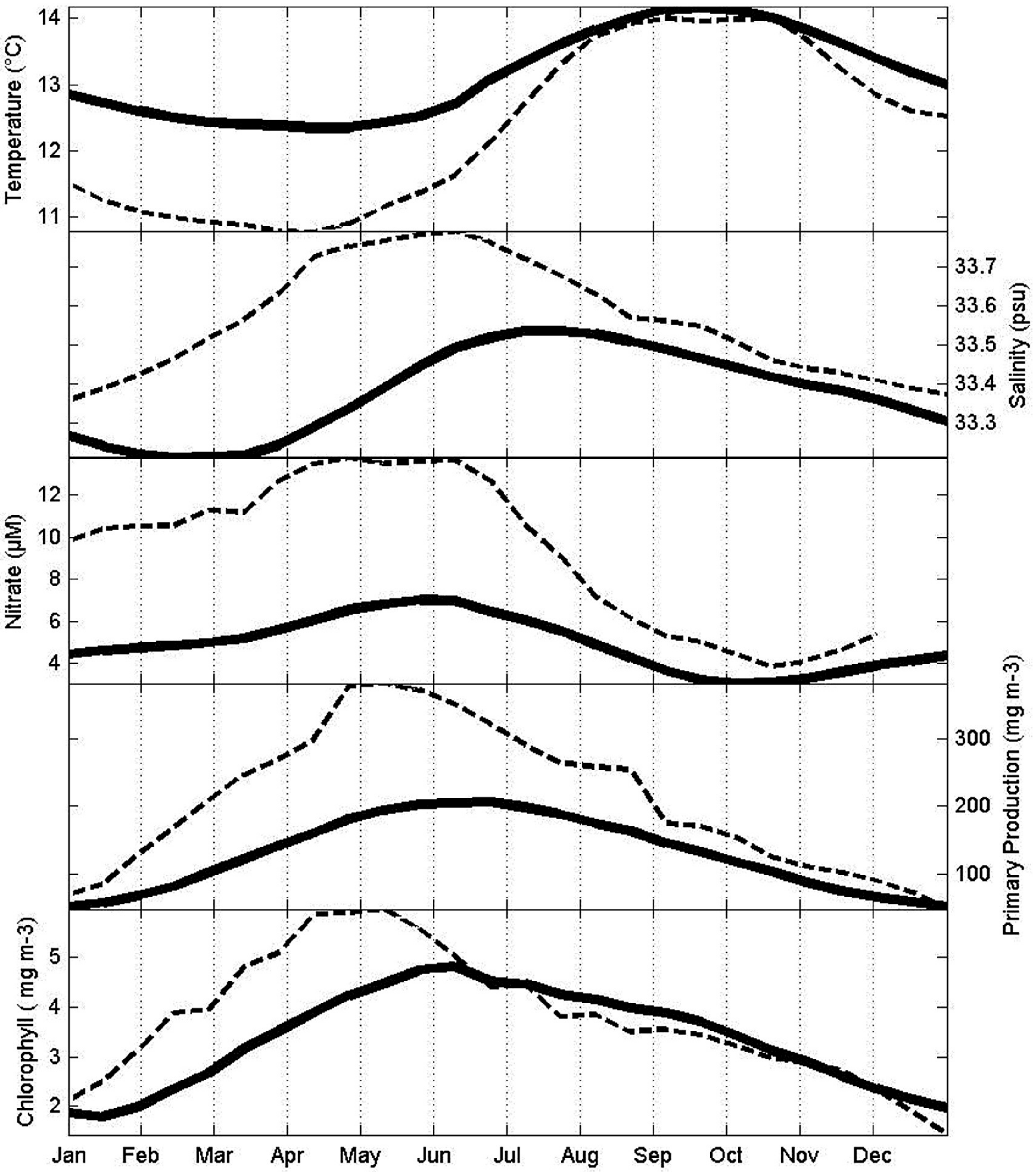

Figure 12. Annual variability in Monterey Bay from hydrographic data. The solid line is the long term mean for 1989–2008 and the dashed line represents measurements from 2008.

such low numbers during the previous warm phase of the PDO that there is an insufficient number of adult spawners to produce dramatic increases in recruits.

Central California Hydrographic Surveys

Along Line 67, the distance of the California Current from the coast varied from 200 km in June 2008 to 300 km in October 2008 and January 2009. This was indicated by the strong gradient of westward-increasing dynamic height observed at the three offshore stations on Line 67. The subarctic character of these waters was also indicated by a salinity <33 at 10 m, temperature <5°C at 10 m at the station farthest from shore and vessel-mounted ADCP measurements which indicated 0.5 m/s south-southwest flow.

Although upwelling-favorable gale force winds occurred in June, the ocean's response seemed to be confined to shallower coastal waters. Despite the strong winds, waters in the upper 50 m remained stratified. High concentrations of Chl *a* in coastal waters confirm the limited extent of the upwelling response to the strong winds. Below 300 m, isopycnals sloped downward toward the

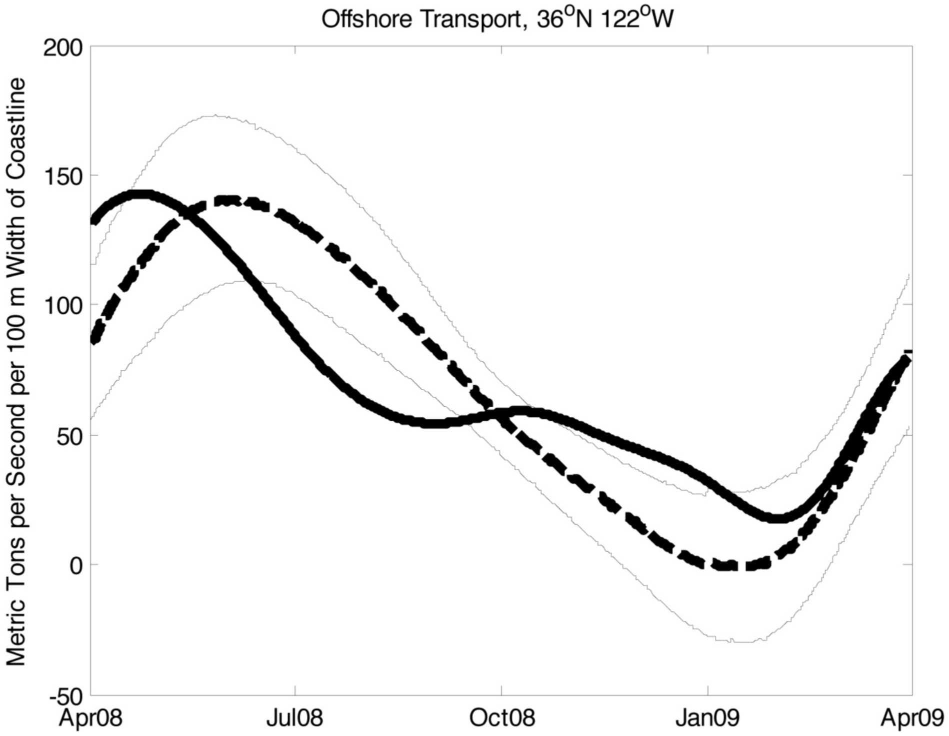

Figure 13. PFEG Offshore Transport at 36°N, 122°W estimated from geostrophic-derived wind stress. Transport for April 2008 to April 2009 is shown by the solid line. The annual mean transport is shown by the thicker dashed line and the variability (± one standard deviation) of the mean is shown by thin dashed lines.

coast within 100 km of the coast indicating poleward flow of the California Undercurrent over the continental slope.

Coastal time series measurements indicated that in late winter and spring 2008, maximum upwelling-favorable wind stress occurred about 1.5 months earlier than usual, resulting in a corresponding seasonal acceleration of the usual cycles of coastal sea surface temperatures, salinities, nitrate, Chl *a*, and primary productivity (fig. 12). This seasonal response is superimposed upon the continuing cool phase of the Pacific Decadal Oscillation, resulting in continued large positive anomalies of nitrate, Chl *a*, and primary productivity. Coastal conditions returned to normal in late summer and fall 2008.

A principle forcing agent of central California waters is offshore Ekman transport of ocean waters caused by alongshore wind stress (fig. 13). The magnitude of the 2008 springtime wind forcing was the same as that of the long-term mean; but the maximum occurred in mid April, about a month and a half earlier than usual. This month and a half lead in the offshore transport cycle continued through August, resulting in less offshore transport in the summer than normal. Offshore Ekman transport during fall was about 50 tonnes/s, larger than normal, and the minimum in February 2009 occurred about a month later than normal. In March and April 2009, offshore transport was almost the same as the long-term mean.

Chavez (2009) described conditions observed in Monterey Bay in 2008 in the context of both global warming trends as well as the continuing cool phase of the PDO. He noted that within the Bay the coolest temperatures in the past 20 years were observed in June 2008 and that primary production continued at high levels in 2008, as documented by a positive seasonal Chl *a* anomaly of about 1 mg/m^3. Sightings of the jumbo squid (*Dosidicus gigas*) by remotely-operated vehicles continued during this cool phase in 2008 at the rate of about 500 per year vs. zero prior to 1998. Values of pCO2 (pH) were ~450 ppm (8), with accelerating upward- (downward-) trends observed in the previous 15 years.

Central California Midwater Trawl Survey

A principal components analysis of fish catches from the annual midwater trawl survey (fig. 14) indicated that the composition of this forage community in 2005 and 2006 was most similar to that observed during the 1998 El Niño, with very low abundances of young-of-the-year groundfish and market squid, but with relatively high catch rates of anchovy and sardine. However, since 2006 the midwater trawl assemblage has trended back towards a species composition more characteristic of the cool, productive conditions experienced in 2002,

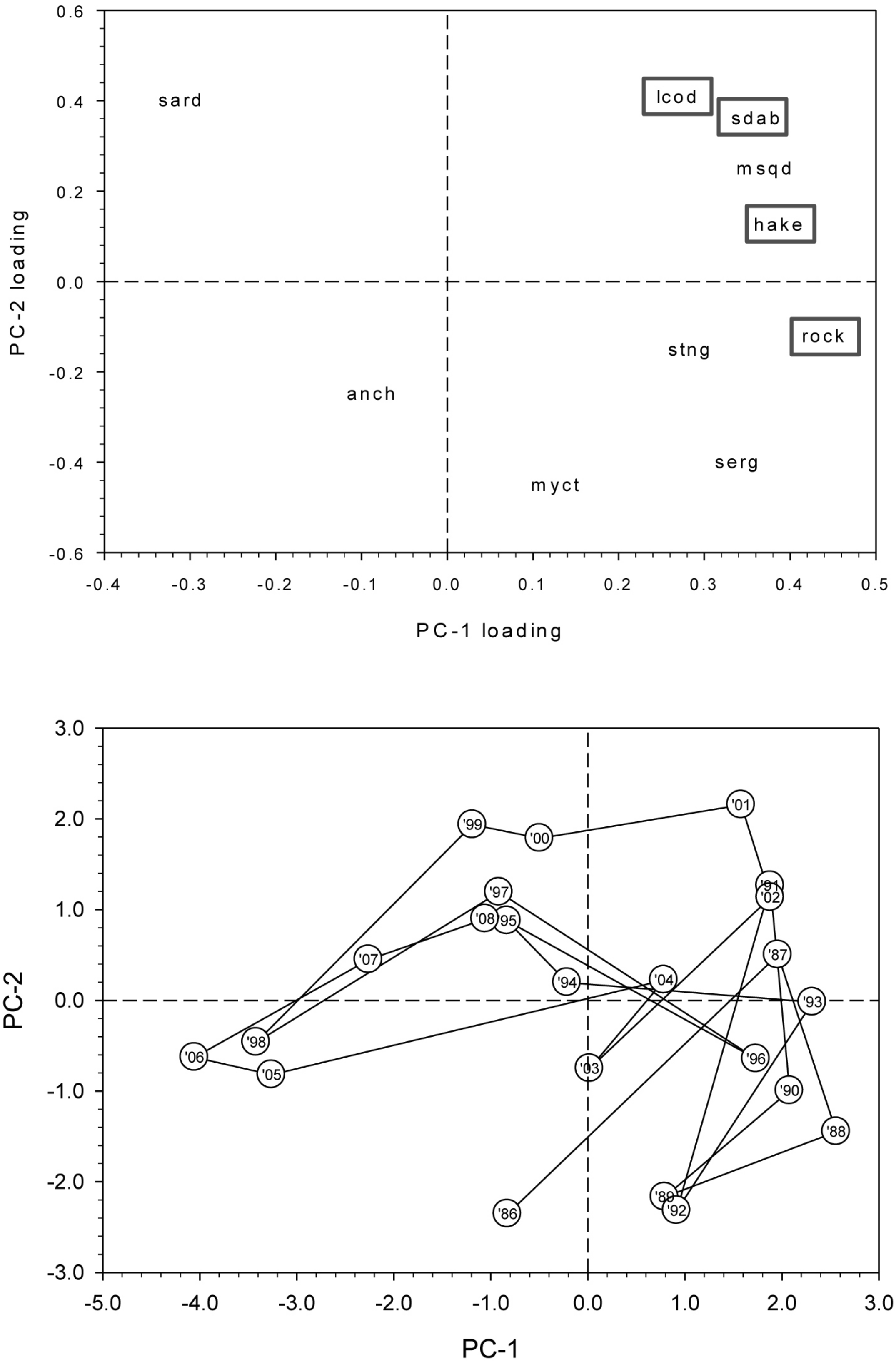

Figure 14. Principal components ordination of the SWFSC Fisheries Ecology Division midwater trawl survey data (1986–2008). The upper panel plots taxon-specific loadings from the first and second eigenvectors (rectangles identify young-of-the-year groundfishes); the lower panel shows the first and second annual principal component scores for the entire assemblage.

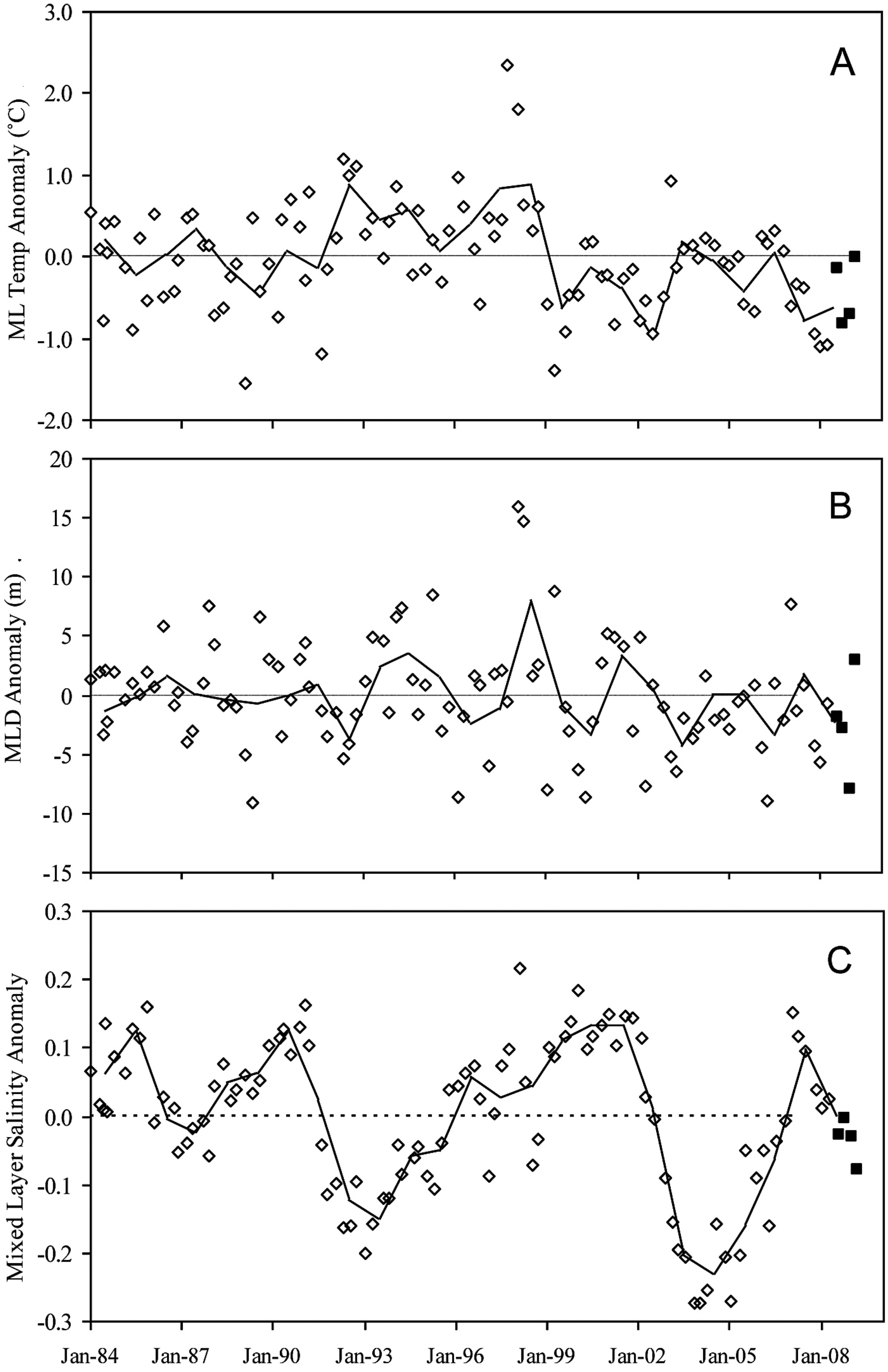

Figure 15. Anomalies of mixed layer (ML) temperature (A), ML depth (B), and ML salinity (C) off southern California (CalCOFI standard grid, Figure 1). Data from the last four CalCOFI cruises are plotted as solid symbols, data from previous cruises are plotted as open diamonds. The solid lines represent the annual averages and the dotted lines the climatological mean, which in the case of anomalies is zero.

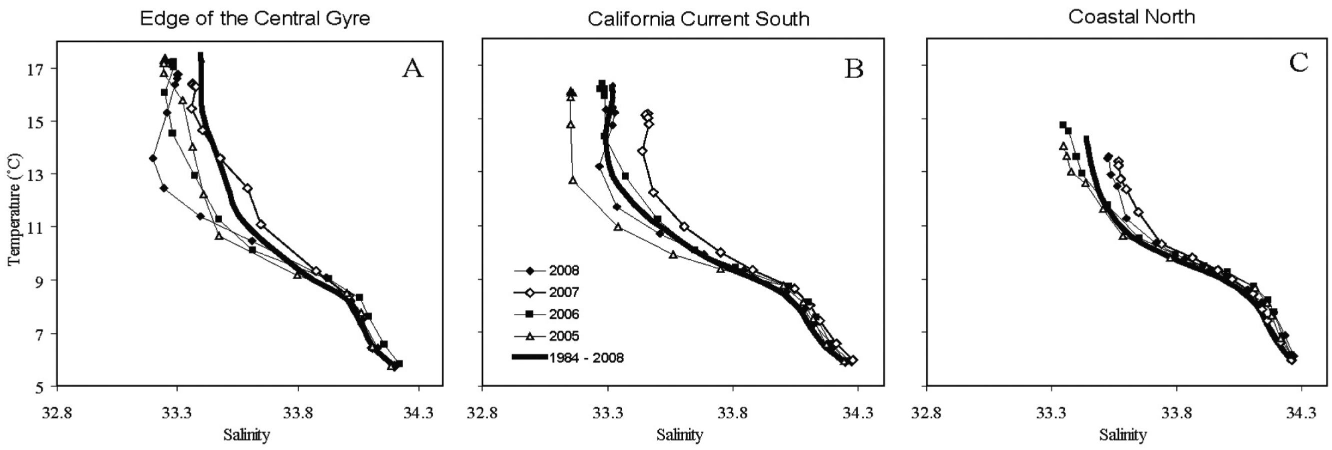

Figure 16. TS plots for three representative areas of the CalCOFI region. A. The edge of the central gyre (Lines 90–93, Stations 100–120), B. the southern California Current region (Lines 87–93, Stations 60-90) and C. the coastal areas in the north (Lines 77–80, Stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time periods, i.e., 1984–2006, 2004, 2005, 2006, and 2007.

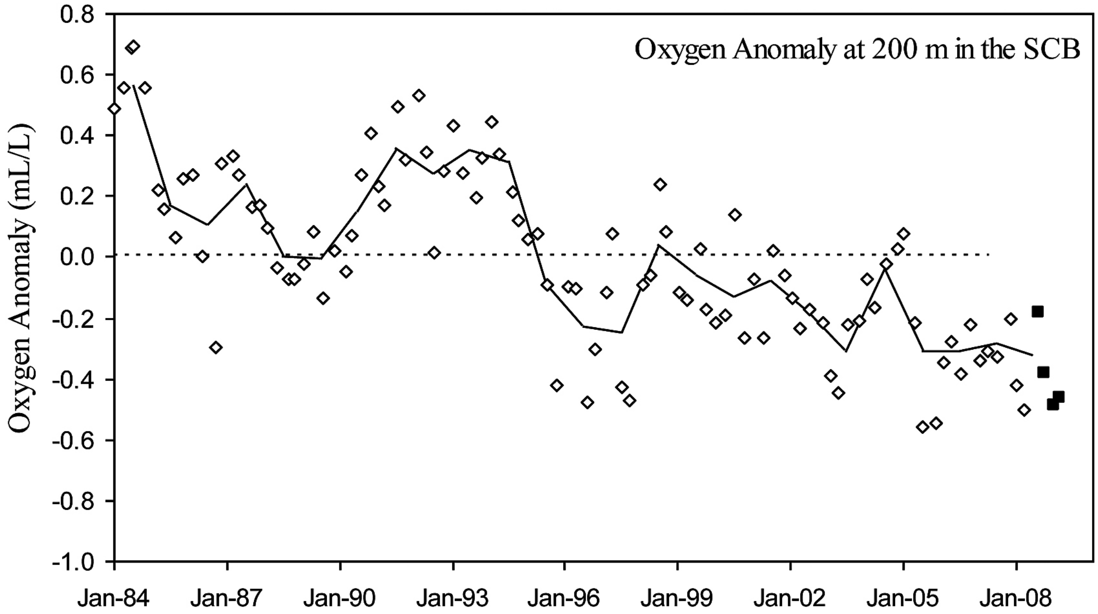

Figure 17. Oxygen concentration anomalies (mL/L) in the Southern California Bight (SCB) at a depth of 200 m. Data are presented as described for Figure 16. It was assumed that all CalCOFI stations along lines 83 to 90 with numbers less than 50 are representative of the SCB.

although the first component score for 2008 remained negative. In a general sense, the species-specific catch rates of the midwater fish assemblage appears to reflect the shift from warmer to cooler conditions that has been observed since 2005.

Northern and Central California Kelp Canopy

In northern California, from Point Arena to the Oregon border, the surface area of the *Nereocystis* kelp canopy in 2008 was the largest in the seven-year record with 7.1 km^2. This region had as little as 0.2 km^2 of kelp canopy in the warm year 2005 and an annual average of 2.9 km^2 in the past. In the central California region, from Point Arena south to Pigeon Point, the surface area of both *Nereocystis* and *Macrocystis* kelp canopy at 7.9 km^2 was also high with 2008 being the second highest in the seven-year record compared with the low in 2005 of 2.3 km^2, and an average of 5.0 km^2.

Southern California

The region covered by the quarterly CalCOFI surveys (fig. 1D) continued to exhibit cooler-than-average temperatures in the upper mixed layer during 2008 and 2009, a pattern observed since 1999 (fig. 15A). Mixed layer temperatures during the second half of 2007 and the first half of 2008 were among the lowest observed since 1984, reflecting the basin-wide La Niña conditions. Mixed layer temperatures during late 2008 and

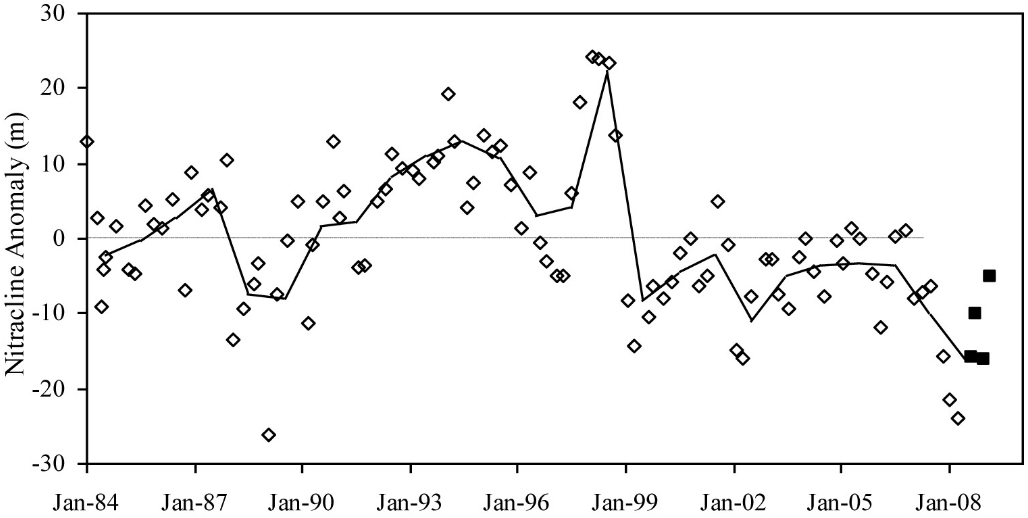

Figure 18. Cruise averages for nitracline depth anomaly. The nitracline depth was assumed to be the depth where nitrate reached values of 1 µM. Data are plotted as described in Figure 15.

early 2009 were similar to those observed over the last decade. Mixed layer salinities were slightly below long-term averages (fig. 15C). Depictions of hydrographic conditions observed during the individual CalCOFI cruises can be found at http://www.calcofi.net.

Temperature and salinity patterns varied across the CalCOFI survey region (fig. 16). In the coastal region north of Point Conception, the mixed layer was anomalously cool and salty in 2008, similar to 2007 but in contrast to 2005 and 2006, when the mixed layer was relatively fresh in this region (fig. 16C). On the other hand, the southern portion of the California Current was relatively cool but salinity did not vary from the long-term mean, unlike 2007, when salinity within the CC was anomalously high (fig. 16B). However, the base of the mixed layer at the edge of the central gyre (the western end of the CalCOFI grid) was fresher than average and also fresher than conditions over the past five years (fig. 16A).

Concentrations of oxygen continued to decline at depth in the Southern California Bight (fig. 17), a trend consistent with the recent report by Bograd et al. 2008. If this trend continues, negative impacts on important fisheries are expected (McClatchie et al. submitted[1]).

Over the last year nitracline depths continued to be relatively shallow, about 10 m shallower than the long-term mean, following a pattern observed since 1999 (fig. 18). In contrast, mixed layer concentrations of the main nutrients (nitrate, phosphate, and silicate) were not significantly higher than average (fig. 19).

Except for the most recent spring cruise (CC0903), standing stocks of Chl *a* averaged over the CalCOFI survey area were near the long-term mean (fig. 20A), following the pattern observed in nutrient concentrations (fig. 19). In April 2009, Chl *a* was anomalously low, likely due to a delay in the initiation of the spring bloom west and southwest of Point Conception. Average annual depth profiles of Chl *a* (fig. 21) show higher than normal concentrations of Chl *a* throughout the euphotic zone in all regions with the exception of the northern coastal region, again reflecting that the spring cruise did not sample a spring bloom. Rates of primary production were variable in 2008, with mean levels relatively high in two cruises and average or anomalously low in the other two (fig. 20B).

Zooplankton displacement volume, which has dramatically declined since observations began 60 years ago (Roemmich and McGowan 1995), followed over the last year the pattern of relatively low mean concentrations observed since about 1993: concentrations even in spring and fall have not increased notably from the low values observed through the winter (fig. 22).

Overall the conditions off southern California in 2008 appeared to follow the cool PDO pattern observed since 1999, with relatively cool, salty conditions in the mixed layer and a shallow nitracline. However, these conditions did not lead to higher nutrient or phytoplankton concentrations in the upper mixed layer, nor have they led to higher zooplankton volumes. This contrasts with observations further north in regions more affected by upwelling.

Southern California Cetaceans

Cetacean visual survey data from spring 2008 through spring 2009 suggest a decrease in overall species diver-

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[1] McClatchie, S., R. Goericke, G. Auad, R. Cosgrove, and R. Vetter. Submitted. Oxygen in the Southern California Bight: multidecadal trends, and implications for demersal fisheries. Submitted to Limnology and Oceanograpy.

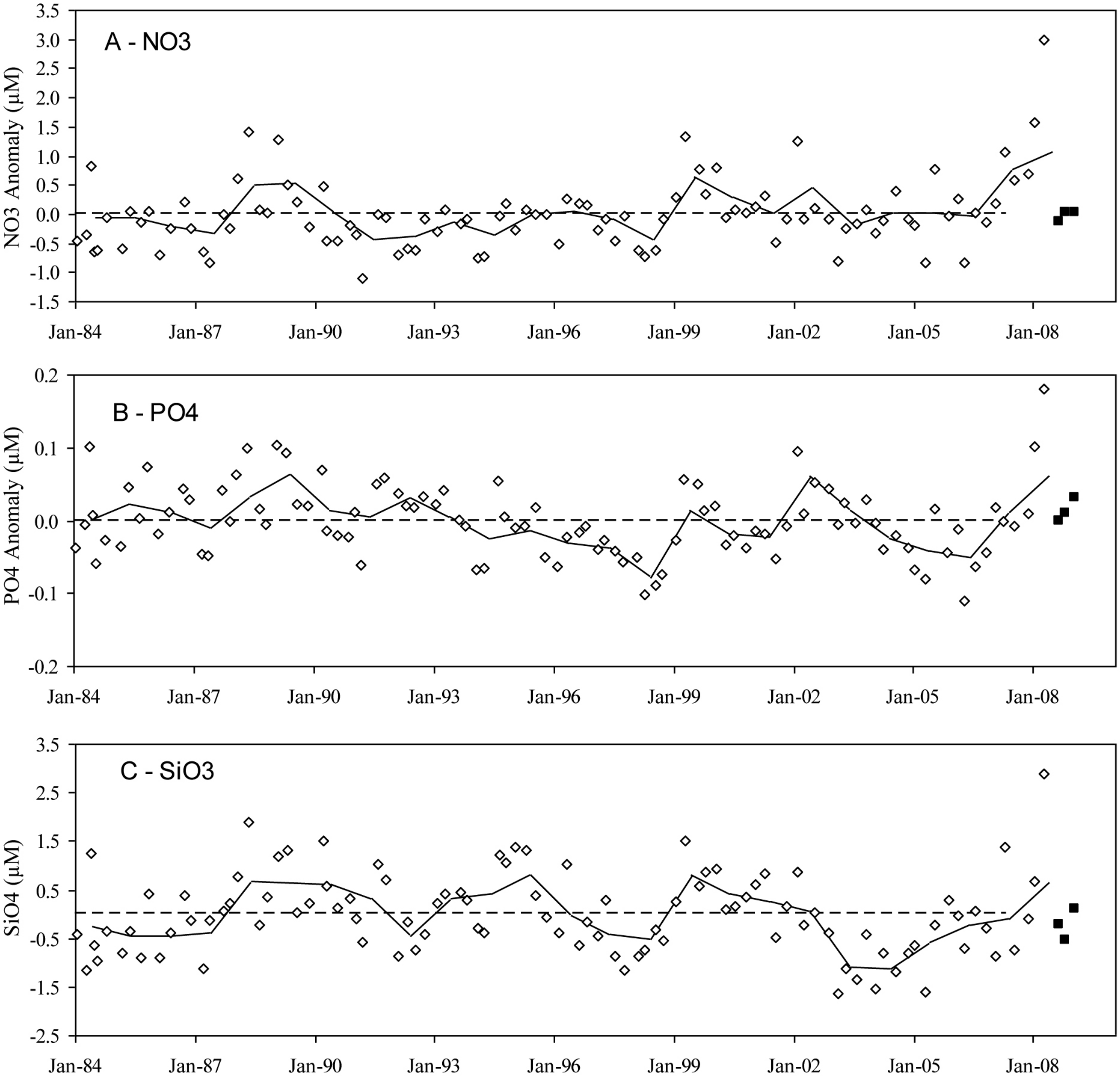

Figure 19. CalCOFI region anomalies for concentrations of (A) nitrate, (B) phosphate, and (C) silicate in the mixed layer. Data are plotted as described in Figure 15. Data for cruise 200904 are not yet available.

sity and changes in abundance for some species within the CalCOFI study area. Species diversity in summer 2008 was lower than usual for the summer season, with observers recording only four dolphin species (including both forms of common dolphins) and five large whale species (including one opportunistic sperm whale sighting). Common dolphin (*Delphinus* spp.) counts were low throughout the year compared to previous years, and blue whale counts in 2008 were the lowest they have been since the initiation of a systematic marine mammal survey effort in 2004. These apparent decreases in animal density may reflect geographic shifts in populations in response to colder than normal temperatures (common dolphins prefer warmer temperatures, Forney et al. 1995), poor feeding conditions (it has been suggested that blue whales are reoccupying former feeding grounds to the north or elsewhere (Dohl et al. 1986; Barlow 1995), and/or other habitat variables. Counts of Dall's porpoise (*Phocoenoides dalli*), a cold-temperate species, were greater than usual for a winter cruise in 2009. Due to low sample sizes it is difficult to detect statistically significant trends at this time.

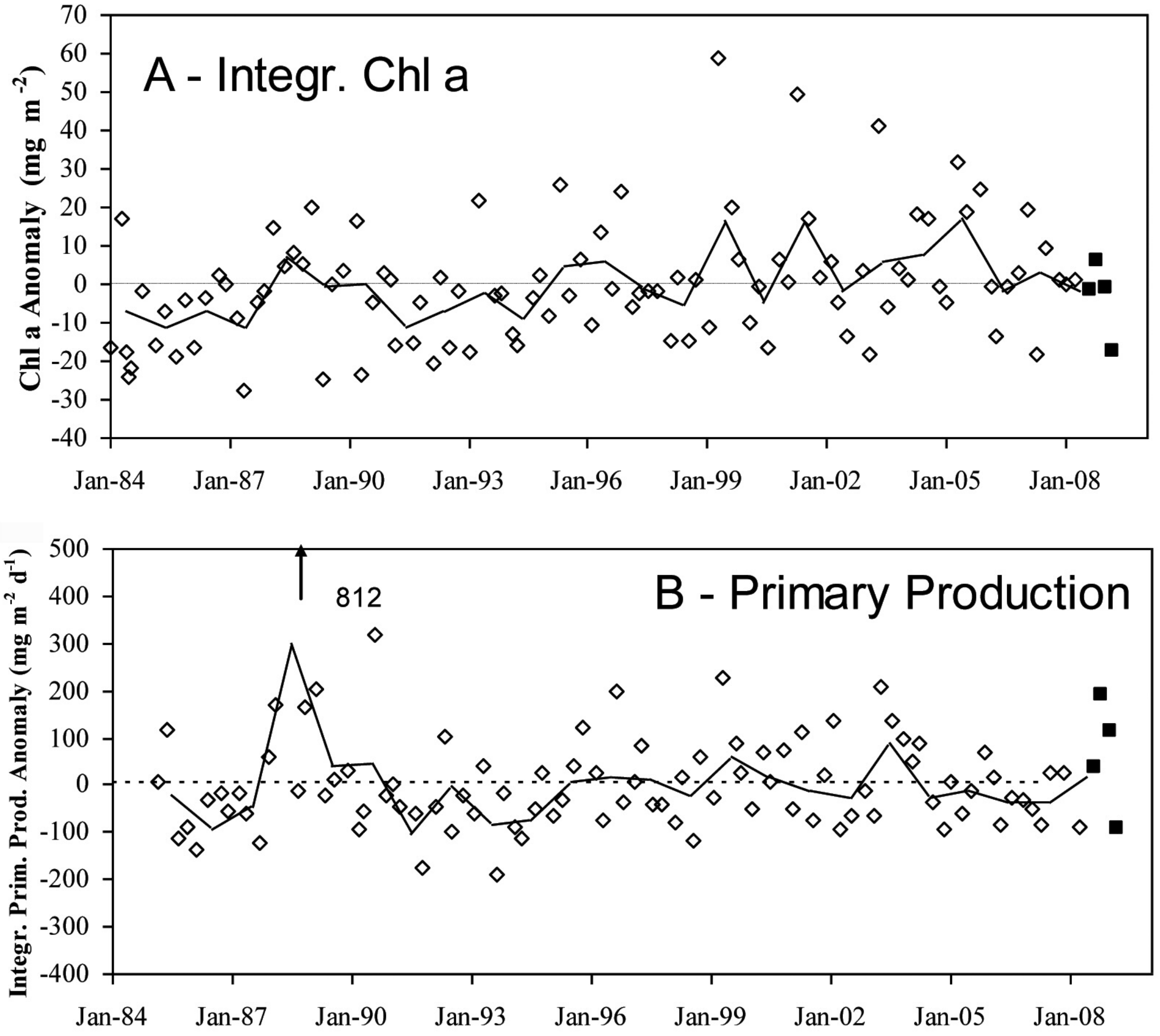

Figure 20. CalCOFI region averages for standing stocks of Chl *a* (A) and rates of primary production (B) both integrated to the bottom of the euphotic zone, plotted against time. Data and symbol codes are the same as those in Figure 15.

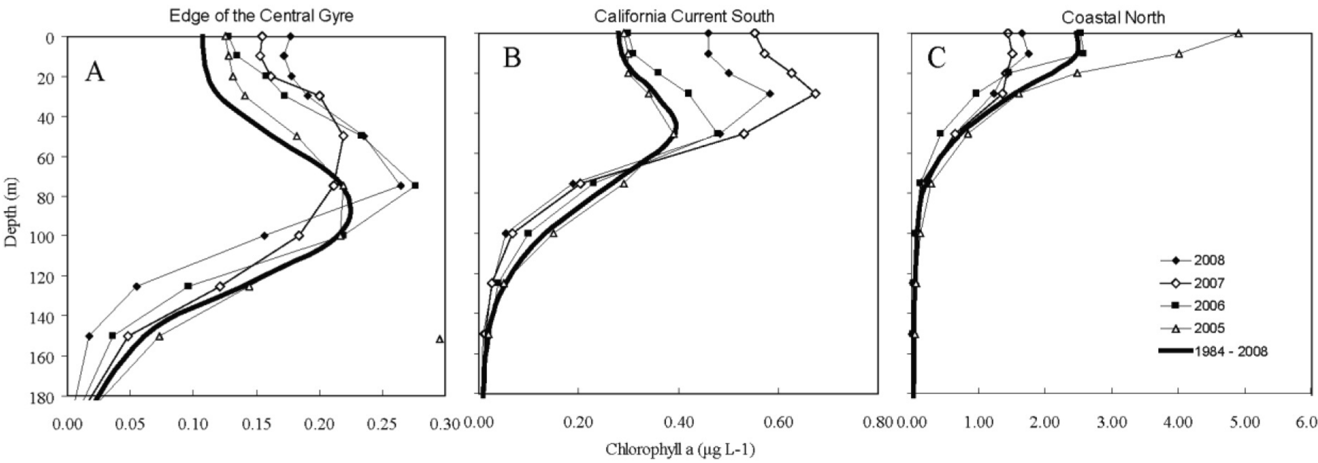

Figure 21. Depth profiles of Chl *a* for the three areas of the CalCOFI region that were described in Figure 1, the edge of the central gyre (A), the southern California Current region (B), and the northern coastal areas (C). Data were calculated and are presented as described in Figure 16.

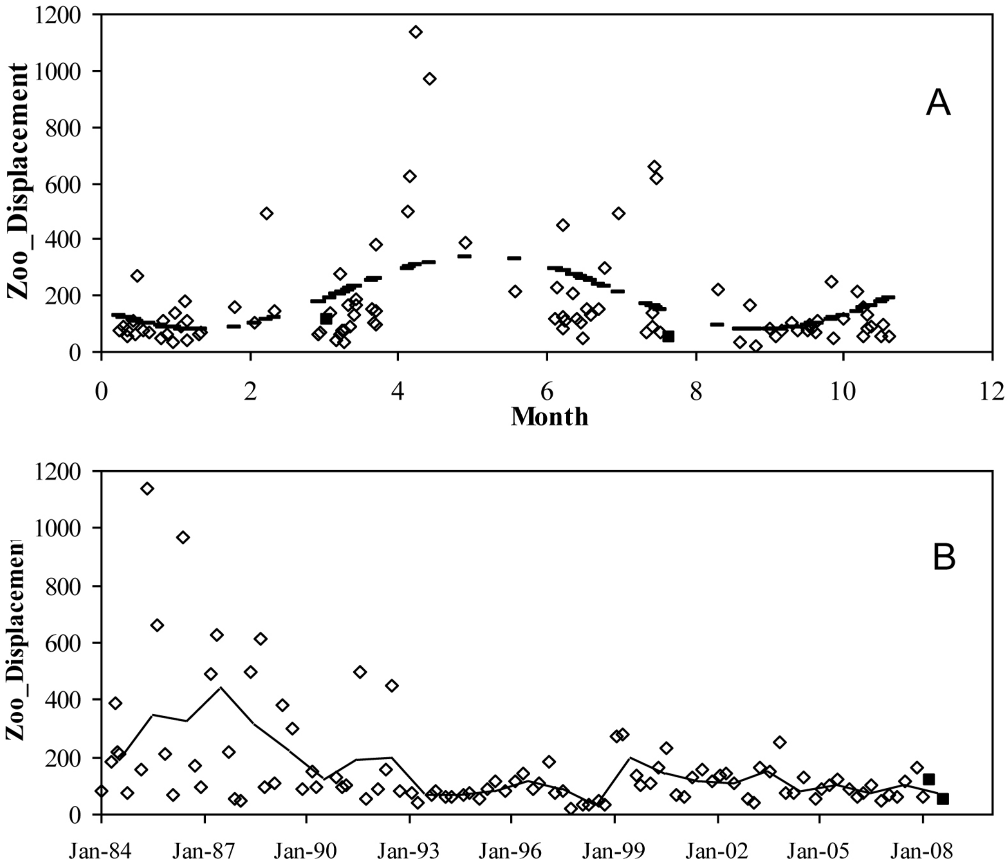

Figure 22. CalCOFI cruise-mean macrozooplankton displacement volumes plotted against the month of the year (A) and time (B). Annual averages are connected by thin solid lines.

NOAA Coastwide Surveys

In April 2008, Pacific sardine eggs were found at sea surface temperatures (SST) greater than 10°C and less than 15°C in April (fig. 23). Very few sardine eggs were found north of San Francisco (37.9°N), and no eggs at all were detected north of Point Arena (or north of 39°N) due to cool surface temperatures. Sardine eggs were found in offshore waters to the south of San Simeon (36°N) where surface waters were warmer (fig. 23). Highest concentrations were found between 30°–35°N, but few eggs were found in Mexican samples off northern Baja California, Mexico (unpublished data). A full time series of sardine, anchovy and mackerel egg maps are available at <http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=1121>.

Sardine spawning is now concentrated in the spring and consequently very few sardine eggs were found anywhere along the entire U.S. west coast during the July/August survey (fig. 24). However a few sardine eggs were encountered at the most southern location sampled in waters as warm as 19°–20°C SST (fig. 24) and a few sardine eggs were also found offshore of the Columbia River where SST was 15°–16°C (fig. 24).

The area north of 40°N latitude has rarely been sampled for ichthyoplankton. The high concentration of sardine eggs off southern California indicates that the spawning ground in 2008 was similar to 2006 and 2007 (Lo et al. 2007; McClatchie et al. 2008), in contrast to 2002–05 when eggs were concentrated farther north off central California.

The cooler conditions did not appear to prevent adult sardine from migrating north after spawning. In April, adult sardine were caught in trawls south of 34°N and west of 120°W, mainly in the same areas where eggs were collected (fig. 23). By July/August no sardine at all were caught south of 37°N. Virtually all catches of sardine were north of 40°N (fig. 24), and were inshore, consistent with the concept that sardine leave their spawning ground and migrate to feed in the more productive inshore coastal regions further north.

The spawning biomass of Pacific sardine is positively related to the daily egg production, in particular if the number of weight-specific oocytes in spawning female fish remains constant (Lo et al. 2008). The relationship between the daily egg production (0.05/m^2) and the average sea surface temperature (°C) during 1994–2008

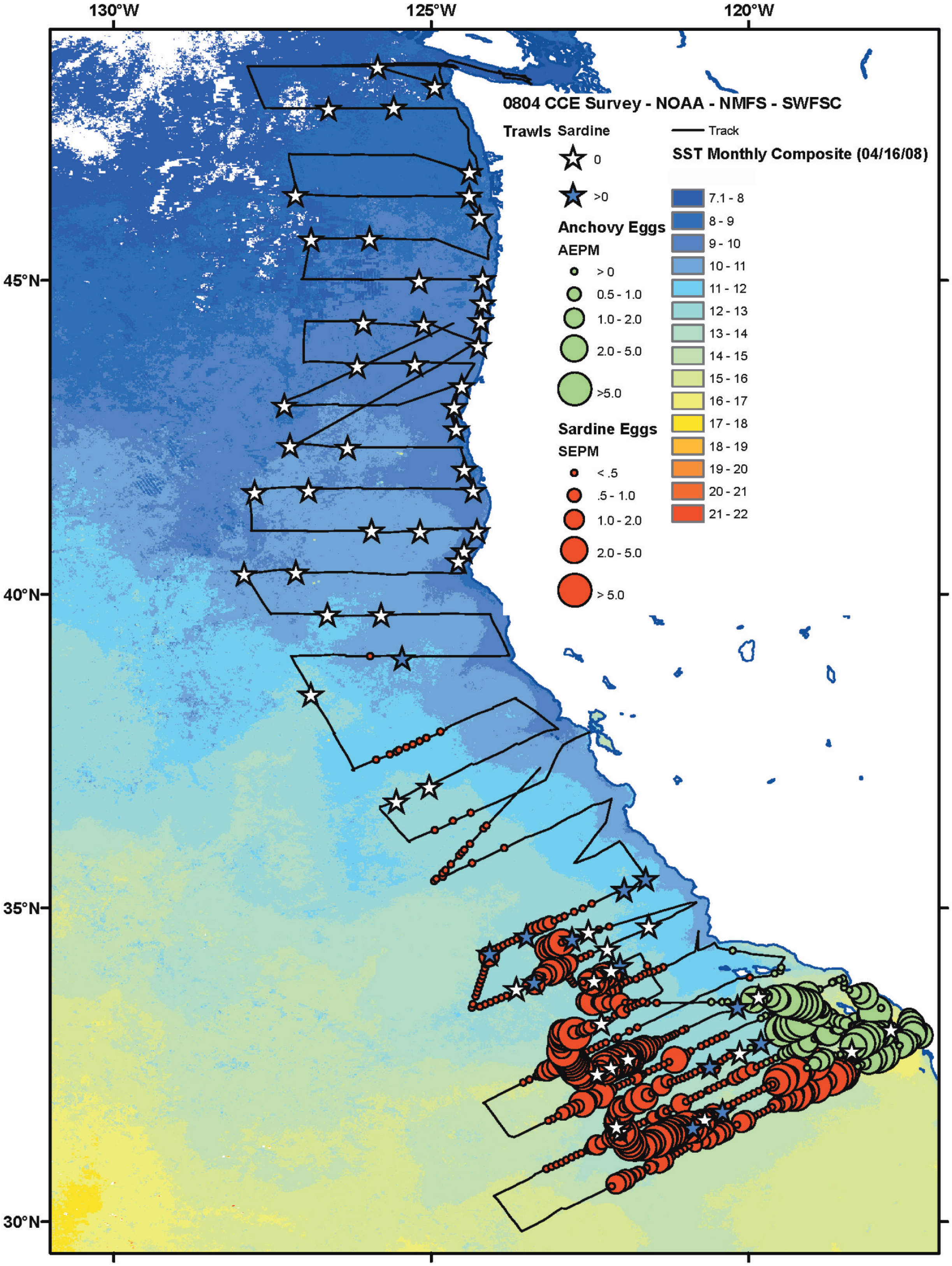

Figure 23. Egg distributions from CUFES and the locations and catches from surface trawls overlaid on a month-long composite of sea surface temperature (satellite SST) for the April 2008 survey. Blue stars indicate positive catches of Pacific sardine (*Sardinops sagax*), white stars indicate no catch of sardine.

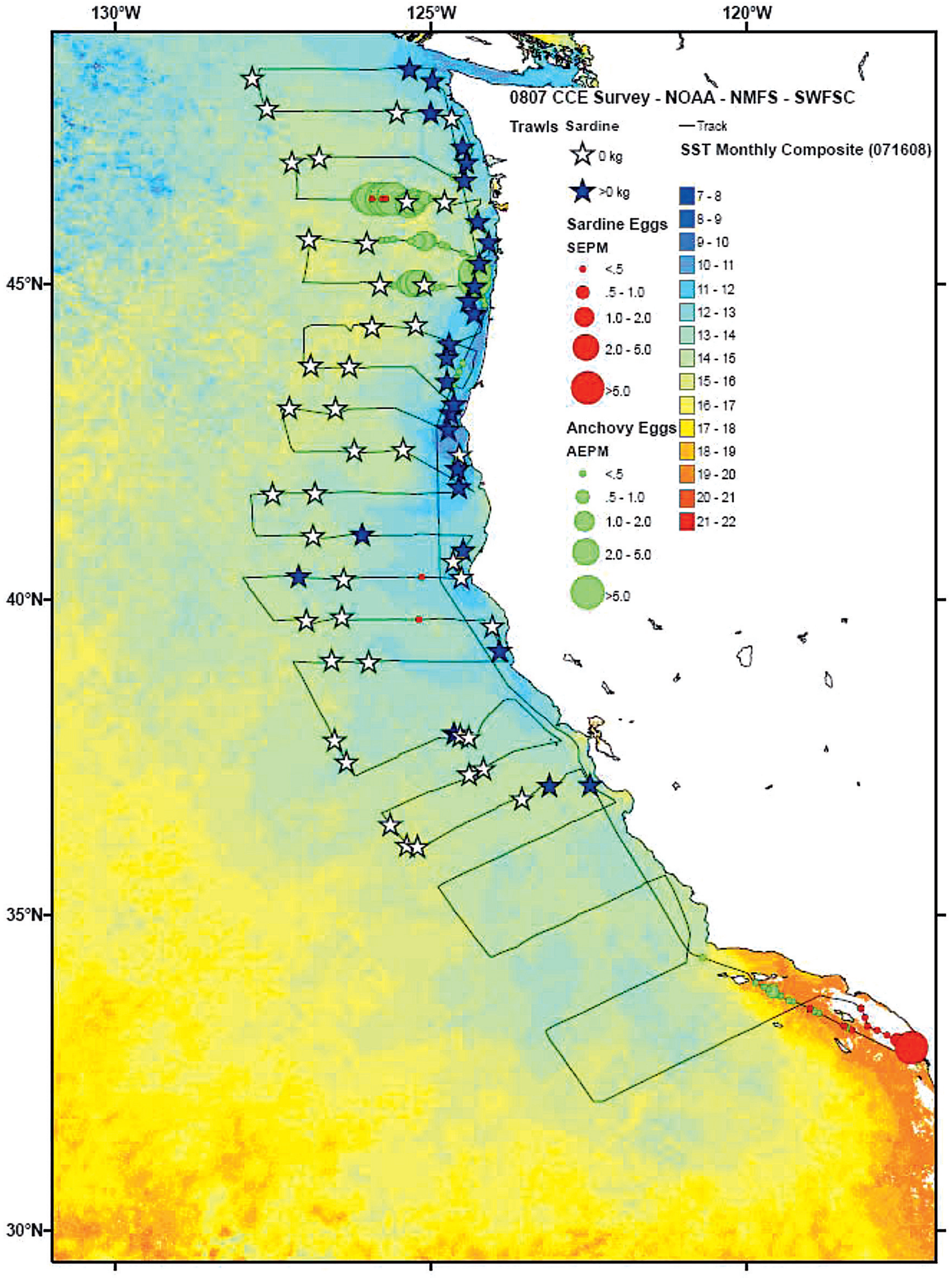

Figure 24. Egg distributions from CUFES and the locations and catches from surface trawls overlaid on a month-long composite of sea surface temperature (satellite SST) for the July/August 2008 survey. Blue stars indicate positive catches of Pacific sardine (*Sardinops sagax*), white stars indicate no catch of sardine.

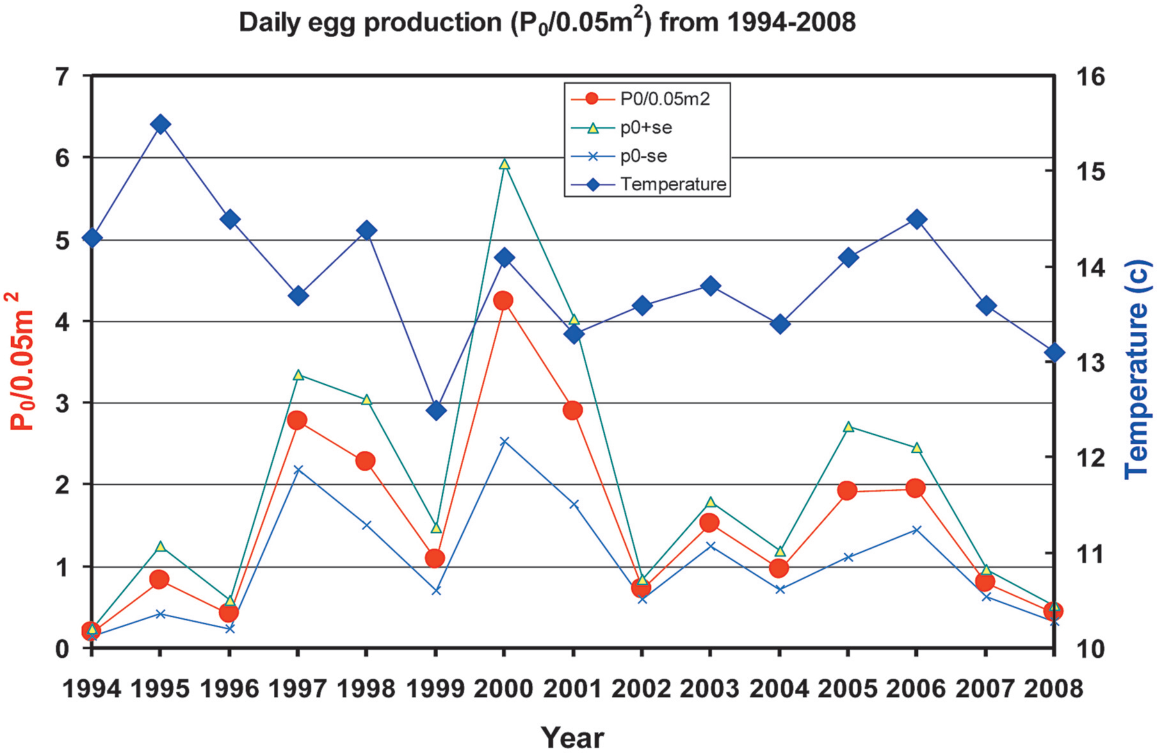

Figure 25. Daily egg production/0.05 m² of Pacific sardine (*Sardinops sagax*) (circle) with upper (triangle) and lower (cross) 95% confidence limits and average sea surface temperature (°C) weighted by egg abundance (diamond) during March–May CalCOFI cruises and DEPM surveys from 1994–2008 for the DEPM survey area between San Diego and San Francisco.

indicated that in most years, except 1997 and 2002, increased daily egg production coincides with increased sea surface temperature (fig. 25). This relationship is consistent with the assertion that warm temperature is favorable for the Pacific sardine (Jacobson and MacCall 1995).

Northern anchovy eggs were abundant in the Southern California Bight (SCB), inshore of the sardine eggs in April 2008; no anchovy eggs were found north of the SCB in April (fig. 23). During the July/August survey a few anchovy eggs were found in the SCB, but the highest concentrations were found off Oregon and Washington at 45°–46°N (fig. 24).

Baja California

Off Baja California the effects of basin-wide La Niña conditions on SST were evident only during early 2008 (figs. 9 and 26); SSTs were close to long-term averages during the rest of 2008. None of the biological variables (Chl *a*, zooplankton biomass or the abundance of copepods or euphausiids – fig. 27) responded to the 2007/08 La Niña conditions. However, a strong covariation was observed between sea surface salinity (SSS) and Chl *a* (fig. 26) over the last decade. The exceptions are October 1997, January 1998 and the year 2007, due to invasion of equatorial water of a high salinity close to values of the undercurrent salinity (Durazo and Baumgartner 2002). The relationship between Chl *a* and zooplankton biomass has changed over the last two years. During 1999–2006 the two measures were negatively correlated ($r^2 = 0.349$). In contrast, anomalies for both measures have been positive during 2008.

Over the last decade zooplankton biomass covaried with the surface to 200 m salinity gradient (fig. 27), a proxy for stratification. The time series consists of two distinct periods, a period of weak stratification (and low zooplankton biomass) during July 1998 to January 2003 and a period of strong stratification (and high zooplankton biomass) during April 2003 to July 2008. Exceptions to these patterns were observed during the El Niño of 1997/98 and 2007 equatorial El Niño. The abundances of the main suspension-feeding crustaceans (copepods and euphausiids) were above long-term averages over the last four years (2004–08; fig. 26); these time series do not show a distinct response to basin-wide forcing, i.e., ENSO or salinity signals. The covariation between copepod abundance and the salinity gradient was not as strong as that observed for total zooplankton biomass but was still significant ($F = 5.0$, $p = 0.031$ when weak and strong stratification periods were compared). Euphausiids did not show significant differences between stratification periods and showed considerable variability.

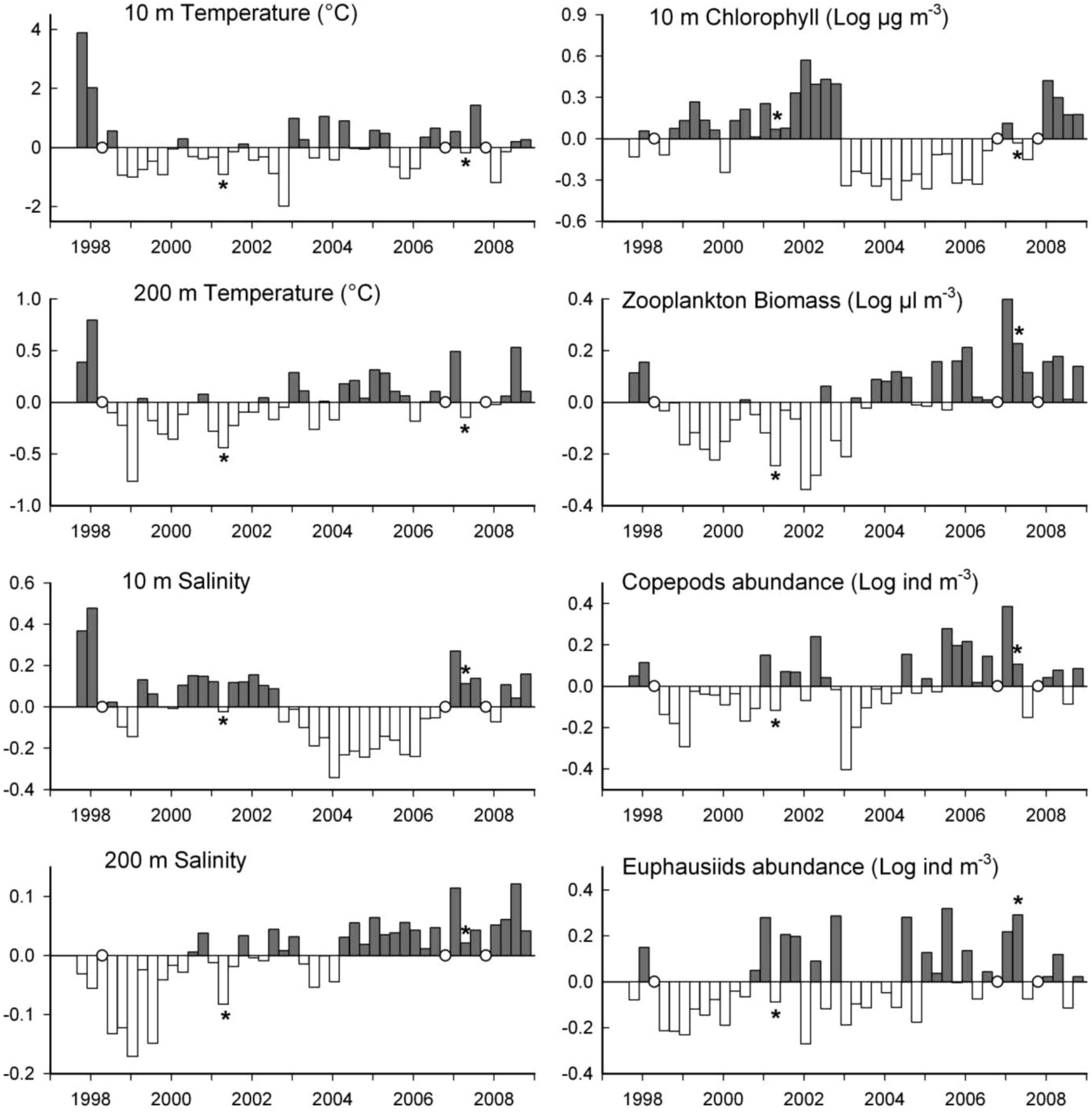

Figure 26. Time series anomalies of hydrological properties at two depths (temperature and salinity), plankton biomass (Chl *a* and zooplankton displacement volume), and nighttime zooplankton abundance (copepods and euphausiids) estimated for the entire area off Baja California. Open circles indicate missing cruises; the asterisks indicate data available only from north Baja California. Biological variables were previously transformed to logarithms.

DISCUSSION

The equatorial La Niña conditions and their extra tropical manifestations along the west coast of North America persisted from the summer of 2007 until the spring of 2009. As typical for these conditions, SSTs were generally lower than normal along the U.S. west coast and similar or even higher than the long-term average along the coast of Baja California, with the exception of January 2008. In most locations, upwelling was stronger than normal in the spring and early summer, slightly below normal in the summer and slightly stronger than normal in the fall. Thus, the years 2007 and 2008 differed dramatically from the years 2005 and 2006 when delayed and weak upwelling during the spring significantly reduced production off central California and Oregon (Sydeman et al. 2006). The delayed onset of seasonal upwelling in spring 2005 and 2006 (Schwing et al. 2006) has been blamed for poor ocean conditions and biological productivity, and recruitment failures in several populations (Sydeman et al. 2006). Extremely poor

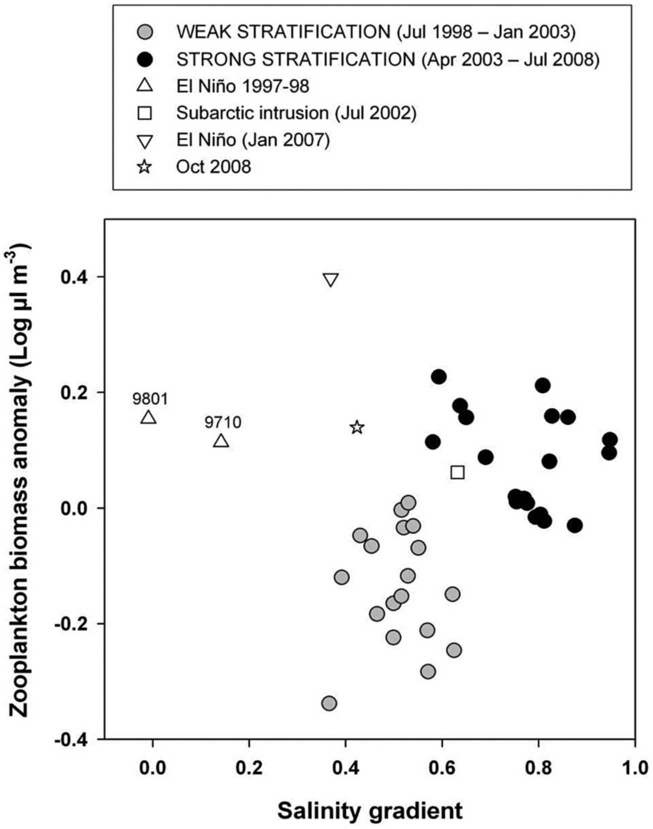

Figure 27. Zooplankton biomass anomaly as a function of the salinity gradient, estimated as the difference between the salinity at 200 and 10 m depth. Symbols indicate two long periods of different stratification conditions and particular events.

returns of fall Chinook salmon stocks in California, which triggered a closure of much of the West Coast salmon fishery, has been attributed to poor production.

In contrast, in 2008 production off central California and Oregon was higher than normal, likely driven by the higher than normal rates of upwelling. The upwelling season began early and remained unseasonably strong through at least April 2007–09 (fig. 5). Cumulative upwelling off central and northern California was particularly high throughout 2008 (fig. 5), and started early in 2009. An implication of this is greater ecosystem production and reproductive success for many populations. In fact, record or near-record returns are expected for Columbia River Chinook Salmon in 2010 (for fish that went to sea in 2008).

However, production off southern California and Baja California over the last four years appeared less affected by coastal upwelling or SST since neither concentrations of Chl *a* nor zooplankton biomass covaried with either variable. Off southern California, concentrations of Chl *a* have been increasing since 1984 and zooplankton displacement volume has been decreasing since the 1950s. Decadal-scale variations in Chl *a* concentrations off southern California have been linked to the North Pacific Gyre Oscillation index (NPGO, Di Lorenzo et al. 2008). As the NPGO reflects changes in large-scale winds and advection, this suggests that off southern California production depends more on basin-scale forcing than coastal upwelling. Observations off Baja California and the analysis provided by the IMECOCAL group (fig. 27) suggest that this is also true for those areas since both Chl *a* and zooplankton biomass covaried strongly with variations of sea surface salinity and salinity gradients, parameters which are driven by forcing associated with the NPGO. To summarize, the data presented in this and previous reports suggest that production north of Point Conception, i.e., in the horseshoe-shaped area characterized by negative SST anomalies during La Niñas, is significantly affected by local SST and coastal upwelling. Areas south of Point Conception appear to be less affected by La Niña conditions and more strongly by basin-scale forcing as reflected by the NPGO.

NOAA Climate Prediction Center (CPC) issued an assessment in July 2009 that El Niño conditions are developing. The criteria used by the CPC for El Niño conditions is a +0.5°C anomaly in the Niño3.4 index, along with consistent atmospheric features, both forecast to persist for three months or more. Since May 2009, positive SST anomalies were recorded across the equatorial Pacific Ocean. While the Niño3.4 index indicates El Niño conditions in the equatorial Pacific Ocean, the criterion for fully fledged El Niño conditions used by NOAA is a +0.5°C anomaly in the Oceanic Niño Index (ONI) sustained over five consecutive overlapping three-month periods. This has not yet occurred. The April–June 2009 ONI value is +0.2°C. Most ENSO models predict that El Niño will continue to intensify through the northern hemisphere summer, and persist through the winter of 2009–10. The models disagree on the predicted strength of the El Niño, but most predict a moderate to strong episode. See http://www.cpc.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf for more details. We conclude, based on these projections, that change is once again about to come to the state of the California Current.

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Part II

SYMPOSIUM OF
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COPEPOD SPECIES RICHNESS AS AN INDICATOR OF LONG-TERM CHANGES IN THE COASTAL ECOSYSTEM OF THE NORTHERN CALIFORNIA CURRENT

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ABSTRACT

Since at least the late 1960s, the coastal waters of the northern California Current have been warming 0.08°C per decade (summer) and 0.06°C per decade (winter). Over the same time period, for summers when the Pacific Decadal Oscillation (PDO) was negative and when zooplankton samples were available for study, copepod species richness increased from 6.9 species during 1969–73, to 7.8 from 1999–2002, and 8.9 from 2007–08. During summers when the PDO was positive, species richness increased from 9.1 (1990–92) to 12.2 (2003–06). The trend towards warmer sea surface temperatures and higher species richness suggests that the coastal branch of the northern California Current receives less water from the cold sub-Arctic Pacific Ocean and more water from the subtropical water mass offshore of Oregon. These changes have been accompanied by a reduction in survival of coho salmon (*Oncorhynchus kisutch*) from the 1970s (range of 6%–12%) to an average of 3% over the past decade. Significant correlations between copepod species richness and coho salmon survival suggest that a time series of species richness may be sufficient to create an index for changes in food-chain structure.

INTRODUCTION

The California Current Ecosystem (CCE) is designated as one of eight large marine ecosystems (LMEs) within the U.S. exclusive economic zone. However, the CCE is not a single ecosystem rather it is composed of many connected ecosystems as a result of strong latitudinal and longitudinal gradients in physical forcing and biological response. The northern end of the current is dominated by strong seasonal variability in winds, temperature, upwelling, and plankton biomass, whereas the southern end of the current has much less seasonal variability in these parameters. The northern end of the CCE is usually dominated by sub-arctic boreal fauna whereas the southern end is dominated by tropical and sub-tropical species. The two regions are separated by two faunal boundaries, i.e., regions where changes in species composition are more rapid: in the waters between Cape Blanco, Oregon and Cape Mendocino, California, and in the vicinity of Point Conception, California.

Highly variable and strong climate signals have been observed recently throughout the California Current, which are affecting ecosystem structure. For example, during the past 30 years, the California Current experienced a prolonged warm event (1989–96), the largest El Niño of the past century (1997–98), two strong La Niña events (initiated in 1999 and 2008), a four-year period of strong upwelling, cold ocean conditions and high productivity from 1999–2002 (Peterson and Schwing 2003), and four years of weak upwelling, warm ocean conditions and reduced biological productivity (2003–06). This recent period of warm ocean conditions reached a climax in 2005, when an unusual delay of upwelling from its usual start in April or May to mid-July (Kosro et al. 2006; Pierce et al. 2006) led to an increase in subtropical zooplankton species in the northern California Current (Mackas et al. 2006), declines in zooplankton biomass and a collapse of the food chain (Hooff and Peterson 2006), along with widespread deaths and nesting failure of many seabird species (Sydeman et al. 2006; Parrish et al. 2007). Survival of salmon stocks that went to sea during the spring and summer of 2005 and 2006 became so low that the salmon fishery was closed coastwide during the summer of 2008. These observed changes in ocean conditions are correlated with the Pacific Decadal Oscillation (PDO) as well, with warm (cold) conditions associated with warm-phases (cold-phases) of the PDO; and cold (warm) phases result in good (poor) salmon survival (Mantua et al. 1997; Peterson and Schwing 2003).

Abrupt changes notwithstanding, ongoing long-term monitoring throughout the California Current suggests that more subtle but measurable changes have taken place in both physical and ecosystem structure over the past 30–40 years. Physical changes include a general warming of the water column and increased water-column stratification (Bograd and Lynn 2003; Huyer et al. 2007; Lavaniegos and Ohman 2007), shoaling of the oxycline, and decreased oxygen concentrations (Chan et al. 2008; Bograd et al. 2008). Biological changes in the southern California Current include decreased biomass of zooplankton (McGowan et al. 1998; although the biomass changes have since been shown to be due to long-term changes in salp composition by Lavaniegos and Ohman 2007), an increase in the abundance of southern and tropical euphausiid species in the southern California Bight, a decreased abundance of a northern species, *Thysanoessa spinifera* (Brinton and Townsend 2003), and increased abundances of oceanic larval fish in the southern California Current (Hsieh et al. 2005).

For the northern California Current, biological changes include earlier maturation of *Neocalanus plumchrus* C5 off Vancouver Island (Mackas et al. 2007) and Oregon (Liu and Peterson, in press), higher abundances of subtropical copepod species and increased biodiversity of copepods (Hooff and Peterson 2006) off Oregon, highly variable salmon runs (Peterson et al. 2006), increased abundance of sardines (*Sardinops sagax*; Emmett et al. 2005), the first records of spawning by hake (*Merluccius productus*), a fish which normally spawns in the southern California Current (Phillips et al. 2007), and an invasion of the voracious Humboldt squid (*Dosidicus gigas*; Field et al. 2007). Albacore tuna (*Thunnus alalunga*), a fish that populates the North Pacific Ocean subtropical gyre, now occur far closer to shore than during the 1970s and have become a major regional fishery in the Pacific Northwest. Other examples can be gleaned from the annual CalCOFI "State of the California Current Reports" (e.g., McClatchie et al. 2008). Taken as a whole, these changes suggest that the northern California Current is slowly becoming more sub-tropical in nature.

Because of long-term changes in physical and ecosystem structure of the California Current towards a more subtropical ecosystem, and the impacts of recent high frequency variability in physical forcing on lower and upper trophic levels, managers have become increasingly interested in receiving regular and timely updates on ocean conditions. They ask if there are components of the ecosystem that can be monitored easily and if there are ways to report regularly on significant changes in the state of the California Current rather than through the peer-reviewed literature. The purpose of this contribution is to demonstrate that change in zooplankton species composition alone is a good candidate as an indicator of change in ecosystem structure. This is based on Peterson and Schwing (2003) who showed that the Pacific Decadal Oscillation is correlated with the biomass of "northern copepod species" (*Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis*), and that the biomass of these northern species is in turn correlated with coho salmon survival. Moreover, Hooff and Peterson (2006) showed that there was a significant correlation between the monthly value of the PDO and both the monthly averaged sea surface temperature (SST) off Newport, Oregon as well as copepod species richness.

This information is now used to produce outlooks of the success/failures of salmon runs in the Pacific Northwest, one year in advance, and is posted to the Web at http://www.nwfsc.noaa.gov (click on "Ocean Index Tools"). Environmental information posted to this site gives managers the opportunity to track both changes in physical oceanographic conditions and food-chain structure in coastal waters of the California Current off the Pacific Northwest. Moreover, similar information is posted quarterly at http://www.pacoos.org (click on "PaCOOS Quarterly Update of Climatic and Ecological Conditions in the CA Current LME"), thus allowing managers and others to track changes throughout the broader California Current on a quarterly basis.

Monitoring zooplankton is a quick and easy way to track changes in ocean conditions and food-chain structure in coastal waters because copepods, being planktonic, are indicators not only of the presence or absence of different water masses, but also of changes in food-chain structure. That is, when the PDO is in a negative phase, cold ocean conditions prevail in the northern California Current resulting in a lipid-rich boreal copepod community, whereas when the PDO is in a positive phase, warm ocean conditions are present which result in a lipid-poor subtropical community (Peterson and Hooff 2005; Hooff and Peterson 2006). Such an approach is an extension of the "indicator species concept" pioneered by Johnson and Brinton (1963), whereby we use different species groups as both indicators of the presence or absence of warm- or cold-water types and as indicators of the bioenergetic content of the lower trophic level organisms.

In this paper, time series of copepod biomass and copepod species richness previously published in Peterson and Schwing (2003) and Hooff and Peterson (2006) are updated. These updated time series are used to demonstrate that copepod species richness alone (that is, the number of species in a given plankton sample) is sufficient to track changes in the coastal marine ecosystem off Oregon. Furthermore, it is shown that this simple index of ecosystem structure is significantly correlated with the survival of coho salmon which may be useful for salmon managers.

METHODS

The historical data sets upon which this paper is based are derived from sampling along the Newport Hydrographic Line for hydrography (monthly to bimonthly, 1961–72; Huyer et al. 2007), and for zooplankton (sampled biweekly-monthly 1969–73; 1977, 1978, 1983 and 1990–92: Peterson and Miller 1975; Hooff and Peterson 2006). More recent data are from biweekly cruises off Newport, which were initiated in 1996. Historical hydrographic data are derived from water sampling at 10 m intervals throughout the water column using Nansen bottles equipped with reversing thermometers. No hy-

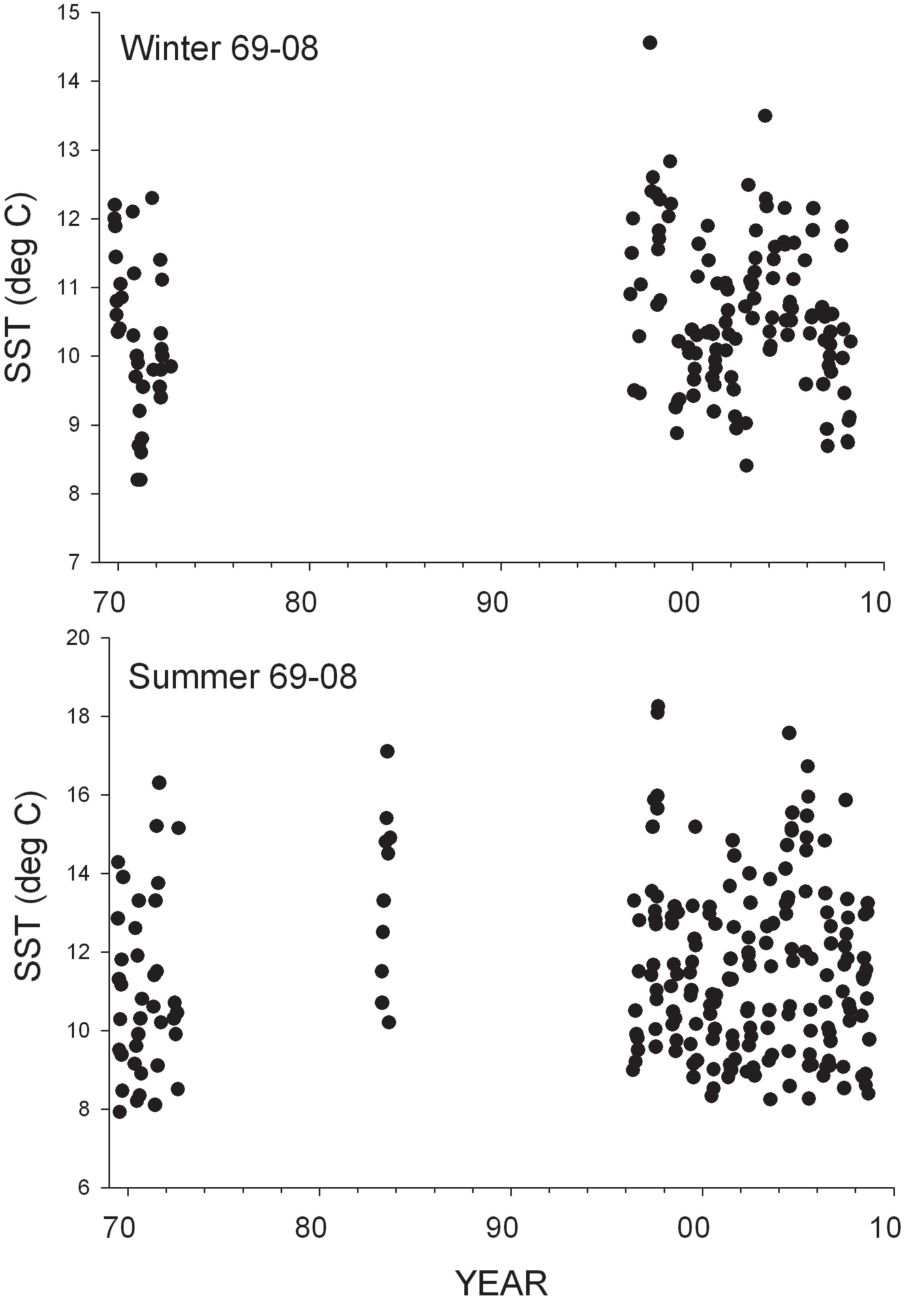

Figure 1. Sea surface temperature at station NH 05 from 1969–73, 1983 and 1996–2008.

drographic data are available for 1977, 1978, or 1990–92. Recent hydrographic measurements were made with a SeaBird SBE 19+ as water-column profiles of temperature and conductivity. Zooplankton was collected with several types of plankton nets over the past forty years: during 1969–73, 1977, 1978 and 1983, the zooplankton was sampled with a 20 cm Bongo net fitted with 240 µm plankton nets and a TSK flowmeter, towed in a step-oblique manner from near the sea floor to the sea surface. In 1990–92 the zooplankton was sampled with a 0.75 m diameter net fitted with a 333 µm net and a TSK flow meter, towed vertically throughout the water column. From 1996 to the present, sampling was with a 0.5 m diameter 202 µm mesh net with a TSK flowmeter, hauled vertically from a few meters off the sea floor to the surface. All of the data shown in this paper are from a single station, referred to as NH 05, located five miles offshore along the Newport Hydrographic (NH) line in 62 m water depth. The station location can be found in recent CalCOFI Reports (e.g., Peterson et al. 2006b; McClatchie et al. 2008). Data from 435 zooplankton samples are presented.

To enumerate the zooplankton, each sample was first rinsed with freshwater, then poured into a graduated cylinder and allowed to settle for at least 30 minutes; then the sample was poured into a beaker and diluted to 5–10 times the settled volume. Subsamples were then taken with a 1 ml piston pipette and all copepods were enumerated by species and developmental stage. At least two subsamples were enumerated (but up to four or five subsamples for those samples with small volumes of plankton) such that a total of at least 400 individuals were enumerated in all subsamples combined. Usually each subsample contained 200–400 individuals. All of the samples were enumerated by the same person (W. Peterson) except for the 1983 samples which were enumerated by another expert (C. Miller) who mentored the other sampler, thus there is not likely to be any differences in the species identifications. All data were entered into a Microsoft Access database; all analyses and plots were done using Sigma Plot 10.0. Species richness is defined here simply as the estimated number of species in a sample.

Other data shown in this paper include the Pacific Decadal Oscillation time series, which is from http://jisao.washington.edu/pdo/PDO.latest, and the time series of coho salmon survival from the Pacific Fisheries Management Council Web site. Members of the Salmon Technical Committee of the Pacific Fisheries Management Council calculated survival data from estimates of the number of salmon released by hatcheries in southwest Washington and northern Oregon and from estimates of the number of salmon caught in the fishery the following year plus the number of salmon that return to the hatcheries and streams to spawn (see Logerwell et al. 2003). The ratio of salmon accounted for in year +1 to salmon released from hatcheries in year 0 is the survival rate. Since most of the marine mortality of coho salmon happens during the first summer at sea (Pearcy 1992), regressions of coho salmon survival with environmental covariates (e.g., copepod species richness) were constructed using the coho survival data lagged by one year.

RESULTS

Figure 1 shows the time series of SST at NH 05 for all data. The range in values was typically 8°–12°C during the winters of 1969–73 but slightly warmer in 1997–2008, at 8.5°–13°C. The range in summer values was 8°–16°C during 1969–73 but slightly warmer during 1997–2008 at 8.2°–17°C. Figure 2 shows the seasonally-averaged values from the same data set for summer (May–September) and winter (October–April). This Figure illustrates that winter and summer averages from the 1960s and 1970s were slightly cooler than recent measurements.

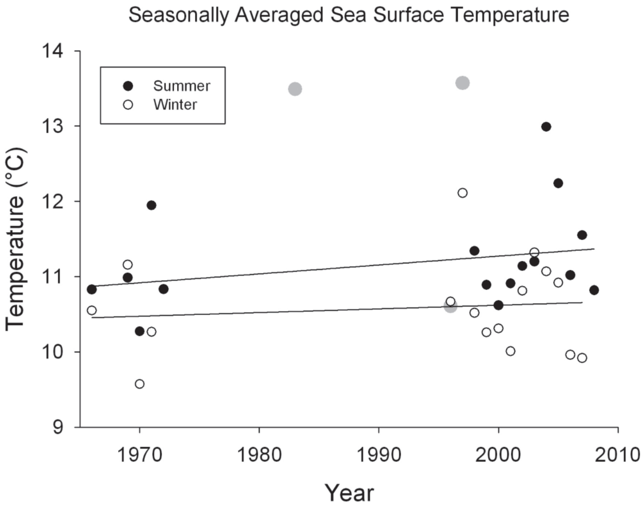

Figure 2. Seasonally-averaged SST at NH 05, for summer (May–September) and winter (October–April). The grey dots are average SST from the two El Niño years, 1983 and 1997. SST was anomalously high during those years; neither was included in the regression analysis. Although neither regression line was significantly different from zero (due largely to the very slight changes in temperature with time), the slopes (indicating the rates of change) are similar to those from the long-term historical records of global SST (see tab. 1).

TABLE 1

Rates of change of sea surface temperature (SST) and at a depth of 50 m at station NH 05 compared to rates of change of global SST, based on summer- (May–September) and winter- (October–April) averaged SST (Newport) and from data shown in IPCC-AR4.

	Deg C per decade	Deg C per 40 years (since 1960s)
All data (summer)	0.078	0.31
All data (winter)	0.056	0.23
Summer average SST	0.118	0.53
Winter average SST	0.049	0.02
Summer T at 50 m depth	0.108	0.43
Winter T at 50 m depth	−0.011	no data
Global Ocean SST	0.18	0.72
Line P SST	0.19	0.76

Regression analysis of SST with time did not reveal that the slope of the trend was significantly different from zero ($p = 0.33$), however, the slopes of the lines were similar to the slope of the trend in global SST reported by the IPCC-AR4 (tab. 1). When all data from NH 05 were combined and analyzed, the overall increase in temperature from 1969 to 2008 (a span of 40 years) was 0.23°C (winter) and 0.31°C (summer). A slightly dif-

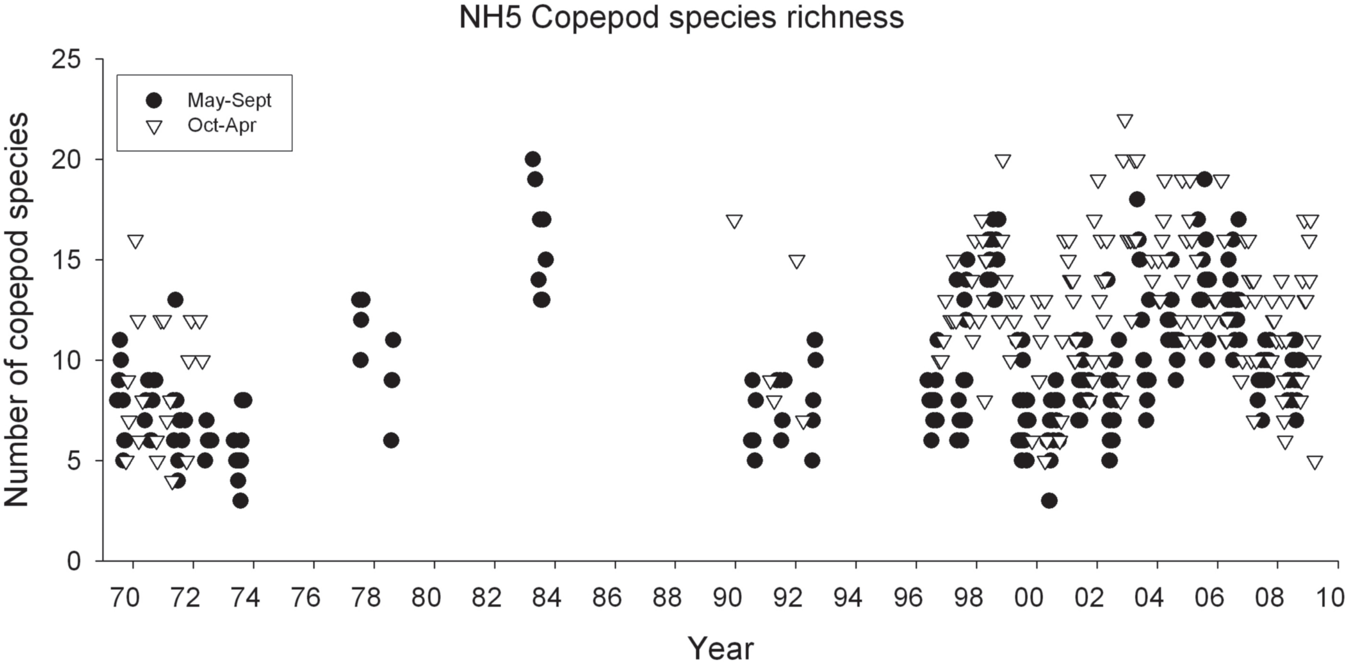

Figure 3. Number of copepod species in zooplankton samples collected at station NH 05, five miles off Newport Oregon, from 1969–73, 1977, 1978, 1983, 1990–92, and 1996–2008. The regression of the number of species on year was significant ($p < 0.001$) but explained only 15% (adjusted R-sq) of the variance. The equation was $y = -0.58 + 0.0003x$. The slope of 0.0003 species per day is equivalent to an increase of 4.38 species over the 40-year time series. Slopes from regressions for summer and winter analyzed separately were the same (4.4 species in 40 years). Data from the 1983 El Niño were excluded from this analysis.

ferent result was obtained when the seasonally-averaged values (summer = May–September; winter = October–April) were regressed one year. This analysis showed that seasonally-averaged SST values at NH 05 have been increasing at a rate of 0.118°C per decade since 1969 during summer, but half that rate in winter at 0.049°C per decade. Similarly, the near-bottom waters at NH 05 in summer have warmed at a rate of 0.108°C per decade but are virtually unchanged in winter at a rate of –0.011°C per decade (tab. 1).

The number of copepod species collected in plankton samples has increased since the first sampling in 1969. Figure 3 shows data collected during 1969–73, 1977, 1978, 1983, 1990–92, and 1996–2008 and although the time series is not continuous, a general increase in species richness is clear. The regression of the number of species on year was significant ($p < 0.001$) but explained only 15% (adjusted R-sq) of the variance. The equation was $y = -0.58 + 0.0003x$. The slope of 0.0003 species per day is equivalent to an increase of 4.4 species over the 40-year time series. Slopes from regressions for summer and winter analyzed separately yielded the same result (4.4 species added over the 40-year period). Data from the 1983 El Niño were excluded from this analysis.

A slightly different result was seen when the number of species were first averaged by season then plotted against year (fig. 4). The regressions were significant (winter = 0.133 species per year; $p = 0.002$; adj. R-sq = 0.52; summer = 0.082 species per year; $p = 0.017$, adj. R-sq = 0.22). The slopes of the regressions were equivalent to adding 5.3 species to the copepod community in 40 years (winter) and 3.3 species to the community in 40 years (summer). The data from the 1983 El Niño event were again excluded from the regression.

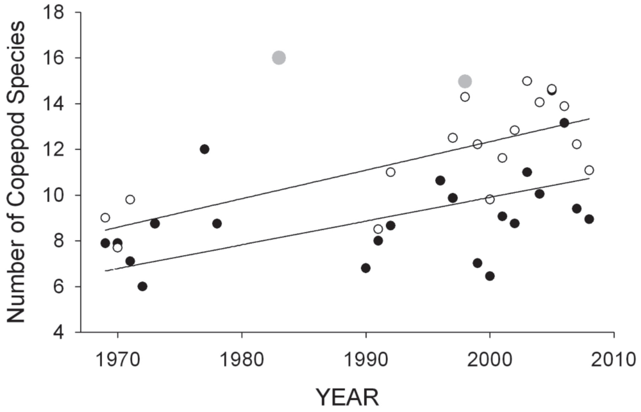

Figure 4. Number of copepod species collected in zooplankton net samples at station NH 05, off Newport, Oregon, plotted against year, for data averaged for summer months (May–September, solid circles) and winter months (October–April, open circles). Regressions were highly significant: winter = 0.133 species per year ($p = 0.002$; adj. R-sq = 0.52); summer = 0.082 species per year ($p = 0.017$, adj. R-sq = 0.22). Slopes of the line are equivalent to 5.3 species in 40 years (winter) and 3.3 species in 40 years (summer). The grey data points are from the 1983 and 1997 El Niño events, and were excluded from the regression.

Interannual differences in species richness were correlated with the Pacific Decadal Oscillation (fig. 5).

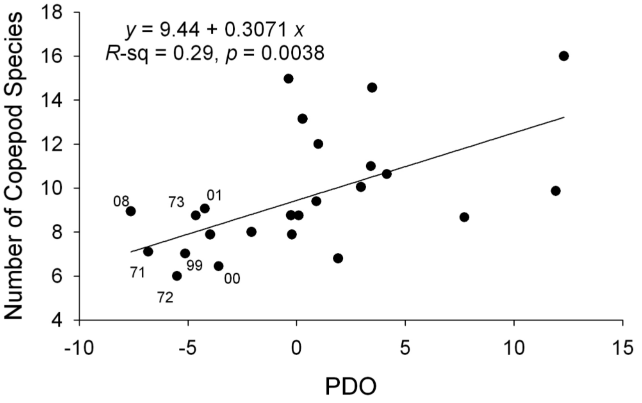

Figure 5. Scattergram showing the relationship between copepod species richness and the Pacific Decadal Oscillation (PDO) during summer months. A warm phase of the PDO results in more species being found at station NH 05, a cool phase, fewer species. Year is identified for those summers when the PDO was strongly negative to illustrate the high diversity observed in 2008 when the PDO had the most negative of all years sampled.

TABLE 2

Number of copepod species in zooplankton samples collected off Newport, Oregon, averaged for summer (May–September) and winter (October–April) months.

Year	Summer	Winter
1969	7.89	9.00
1970	7.89	7.70
1971	7.10	9.80
1972	6.00	
1973	5.50	
1977	12.00	
1978	8.75	
1983	16.00	
1990	6.80	
1991	8.00	8.50
1992	8.67	11.00
1996	10.63	
1997	9.87	12.50
1998	14.97	14.29
1999	7.02	12.22
2000	6.45	9.81
2001	9.07	11.62
2002	8.76	12.83
2003	11.00	14.98
2004	10.05	14.06
2005	14.50	14.64
2006	13.15	13.89
2007	9.40	12.21
2008	8.94	11.08

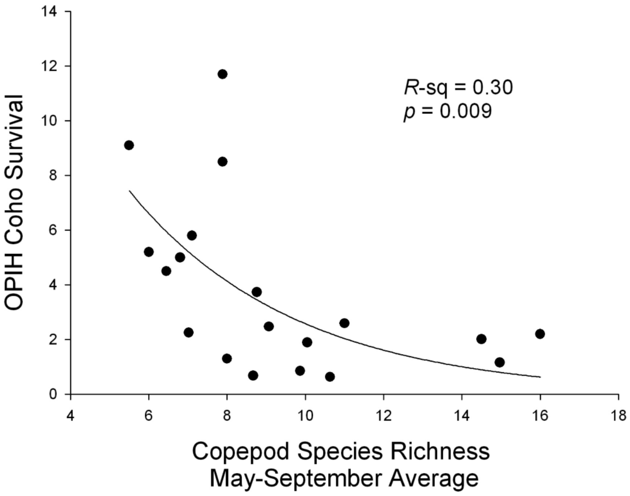

Figure 6. Relationship between survival of hatchery-raised coho salmon and copepod species richness. The plot compares data from the summer that the fish entered the ocean. Coho return to their natal streams/hatcheries 18 months after entering the sea.

During the warm phase of the PDO, more species are found, whereas during the cool phase, fewer species occur. However the PDO accounts for only 30% of the variance, thus other factors contribute to the increase in copepod species richness. The correlation with the PDO must be examined with some caution (especially since less than one-third of the variance in species richness is explained) because during the summer of 2008, for example, the PDO was strongly negative yet species richness was relatively high during that summer (8.9 species) compared to the 1970s (average of 6.9 species from 1969–73, tab. 2). The species which occur most frequently during summers include *Calanus marshallae*, *Pseudocalanus mimus*, *Centropages abdominalis*, *Acartia longiremis* and *Oithona similis*. Recently other "northern" species have occurred more frequently during the summers of 2007 and 2008 as compared to 1969–73, including *Tortanus discaudatus* (17% of samples in 2007–08 vs. 5% of samples from 1969–73), *Metridia pacifica* (62% vs. 47%), and *Microcalanus pusillus* (38% vs. 23%) and *Acartia hudsonica* (86% vs. 74%). Each of these is a subarctic species which might suggest a greater influx of sub-arctic water into the northern California Current (NCC) during 2007, and especially 2008 when the PDO was extraordinarily negative. Since *M. pacifica* and *M. pusillus* are boreal oceanic species, whereas *T. discaudatus* and *A. hudsonica* boreal neritic, this suggests that increased volumes of subarctic water entered the NCC, from both an offshore source as well as along a coastal corridor.

Similarly, the number of species observed during the warm phase of the PDO in summers of 2003–06 (average of 12.2 species for an average PDO score of 2.54) was far more than during the warm phase of the PDO in 1990–92 (9.1 species for a higher PDO score of 3.26). In this case, the species with a greater frequency of occurrence during 2003–06 were *Clausocalanus pergens*, *C. parapergens* and *C. arcuicornis*, whereas none were observed during 1990–92, and *Paracalanus parvus* (12.5% in 1990–92 vs. 98.3% in 2003–06). Thus, despite the positive correlation with the PDO, the increasing number of species with time, especially over the past 10 years, is explained only in part by the PDO.

Finally, interannual differences in copepod species richness were significantly correlated with survival of coho salmon (fig. 6).

DISCUSSION

The surface waters of the coastal northern California Current are warming at a rate of about 0.08°C per decade (in summer) and 0.06°C (in winter). These rates are about one-half the rate of the southern Gulf of Alaska (0.19°C; Crawford et al. 2007) and that of global SST (0.18°C; Domingues et al. 2008). Although the trends in temperature vs. time in the NCC, the Gulf of Alaska, and globally are not statistically significant (due largely to the strong seasonal cycle in temperature), few scientists doubt that the warming trend is real. The slower rate at which the northern California Current is warming compared to global SST is likely related to the influence of coastal upwelling on summer temperatures. Both the Gulf of Alaska and global temperatures are more a function of solar heating whereas coastal waters of the NCC are kept somewhat cooler by upwelling. The observation that coastal waters are warmer now than in the 1970s suggests that coastal upwelling is less intense, however this does not appear to be the case because there is no difference in upwelling at 45°N since at least 1969 (the slope of the linear regression was 0.81 upwelling units per year, but the slope was not different from zero; $p = 0.33$; not illustrated). This clearly does not meet expectations of increased upwelling (Bakun 1990; Snyder et al. 2003) expected with global warming, at least for the waters off central Oregon.

Temperature trends in the CalCOFI region of the southern California Current are similar to the global trend. Bograd and Lynn (2003) found a warming trend of about +1°C since 1950 (equivalent to 0.2°C per decade, the same rate as in the Gulf of Alaska). DiLorenzo et al. (2005) also reported on the same CalCOFI hydrographic data set and found not only a warming of SST by 1.3°C, but a deepening of the thermocline by 18 m, and increased stratification over the period 1950–99. Moreover, through use of a ROMS (Regional Ocean Modeling System), they showed that increased stratification associated with warming reduces the efficiency of coastal upwelling in bringing cold waters up to the sea surface. This in turn has resulted in lesser amounts of nutrients being brought to the sea surface and lower productivity, processes which they suggest may explain the order of magnitude declines in zooplankton biomass in the CalCOFI region (but see Lavaniegos and Ohman 2007 for an alternate view).

Most of the variation in both temperature and copepod species richness in coastal waters off Newport, Oregon, was at the seasonal time scale. These variations are driven by the seasonal cycle in the winds, circulation and coastal upwelling. During the summer, coastal winds blow from the north, causing upwelling along the Washington and Oregon shelf. Shelf waters of Washington and Oregon are cold and salty at this time of the year and boreal copepods are transported along the shelf from a northern source (Peterson and Miller 1975). During winter months, winds are from the southwest, causing seasonal downwelling and coastal currents are northward. Shelf waters are warmer and fresher than in summer as a result of the Davidson Current transporting water from the south and from offshore, bringing with it subtropical copepods from shelf waters off California as well as from subtropical waters which lie offshore of Oregon (Peterson 1972; Morgan et al. 2003).

At the decadal time scale, some of the variability in summer-time species richness is explained by the PDO (which accounted for 30% of the variance). However, given that the gradual increase in species richness since the 1970s broadly matches the general warming of coastal waters of the northern California Current, a hypothesis could be offered that the increased warming and increased species richness are both linked to global warming. But what mechanism would link warming with species richness? As discussed by Hooff and Peterson (2006), one potential (and testable) mechanism that results in an increased number of species is related to the source waters which feed the coastal waters off Oregon. If the source waters which feed the coastal currents include the transport of a greater volume of water from offshore of Oregon, which is subtropical in nature, and which has species richness values on the order of 15–20 species in a zooplankton sample (Keister and Peterson 2003; Peterson unpub. data), then increased species richness in coastal waters would result. Indeed, ROMS studies conducted by Chhak and DiLorenzo (2007) and Keister et al.[1] (in prep) demonstrate that it is the onshore movement of surface waters from offshore Oregon during a positive phase of the PDO that results in increased species richness. This is consistent with conclusions drawn by Hooff and Peterson (2006) who suggested that changes in source waters driven by remote basin-scale forcing, not local environmental events, cause interannual-to-decadal variations in copepod biodiversity in the northern California Current.

The results of the ROMS study by the DiLorenzo group is supported by observations reported by Parrish et al. (2000). They showed that surface waters entering the California Current during 1976–90 (the positive PDO phase) were of sub-tropical origin, due to increased strength of westerly winds. They suggested that remotely-forced variations in surface transport controlled the source and character of the surface waters of the California Current system.

Increased species diversity off Oregon is consistent

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[1] Keister, J. E., C. A. Morgan, N. Mariani, V. Combes, E. DiLorenzo, and W. T. Peterson. In prep. Copepod species composition linked to ocean transport in the northern California Current. University of Washington. School of Oceanography, Box 357940, Seattle, Washington 98195.

with a prediction from global climate models that the distributions of plants and animals will shift northward. Under this expectation, copepod species richness at one geographic point, such as the Oregon coast, should increase simply because of northward shifts in distribution of sub-tropical species. Indeed, this has been observed in the Gulf of Alaska zooplankton from continuous plankton recorder surveys (Mackas et al. 2007) and from our own unpublished work off Oregon (Liu and Peterson, in press), where we've seen that *Neocalanus plumchrus* have been awakening from diapause earlier and are developing faster, and both are correlated with increased temperature. Thus, the overall conclusion is that the northern California Current is gradually becoming more subtropical in nature, albeit at a slow pace, but especially so when the PDO is in a positive phase. Thus, the observed increase in species richness is likely due to a general warming in the coastal zone of the California Current resulting from both a northward and onshore shift in the distributions of copepod species.

The significant correlation of copepod species richness with coho salmon survival matches the high correlation between the biomass of northern copepod species and coho salmon shown by Peterson and Schwing (2003) and by Peterson et al. (2006a) (see "Ocean Index Tools" at http://www.nwfsc.noaa.gov). This suggests that even a very simple index like the number of copepod species in a plankton net sample may be a good proxy index for the "quality" of the food chain in the same manner as suggested by Hooff and Peterson (2006). That is, northern copepods are lipid-rich species (dominated by *Calanus marshallae* and *Pseudocalanus mimus*) whereas southern copepods (dominated by *Calanus pacificus*, *Paracalanus parvus*, *Clausocalanus* spp., *Calocalanus styliremis*, *Ctenocalanus vanus* and *Corycaeus anglicus*) are relatively lipid-poor species. Thus the food chain is anchored by copepods with high-energy density during cold ocean conditions and negative phases of the PDO, whereas the food chain is anchored by copepods with low-energy density during warm ocean conditions and positive phases of the PDO. Biodiversity also changes with the sign of the PDO; as shown in Figure 5, cold conditions have fewer copepod species and warm conditions have a greater number of species. Thus, others working in the California Current may be able to investigate relationships between zooplankton, food-chain structure and fish recruitment simply by enumerating the species in a set of plankton net subsamples, rather than by taking on the far more time-consuming task of carefully enumerating by species and developmental stage. Clearly, the latter would be preferred, but the simpler approach advocated here would add value to any plankton collection. This conclusion is supported by Lavaniegos and Ohman (2007) who noted that measures of biomass are insensitive indicators of climate forcing; the more compelling data sets (and those most associated with climate-change signals) are changes in species composition.

In conclusion, surface waters of the coastal northern California Current are warming at a rate of about 0.08°C per decade in the summer and 0.06°C per decade in the winter. At the same time, for those years when the PDO was negative, copepod species richness increased from an average of 6.9 species during 1969–73, to 7.8 from 1999–2002, and to 8.9 from 2007–08. Likewise during summers when the PDO was positive, species richness increased from 9.1 (1990–92) to 12.2 (2003–06). Significant correlations between species richness and coho salmon survival suggest that this simple measure of copepod community structure is sufficient to index the changes in food-chain structure suggested by Hooff and Peterson (2006).

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SEABIRDS AND CLIMATE IN THE CALIFORNIA CURRENT—A SYNTHESIS OF CHANGE

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ABSTRACT

We investigated changes in ocean climate and ecosystems by reviewing select case histories for seabirds in the California Current ecosystem (CCE) and the transition zone between the CCE and the Gulf of Alaska using data from the early 1970s to the present. We used information spanning the entire CCE, from the south (California Cooperative Oceanic Fisheries Investigation [CalCOFI]) to the north (Ocean Station Papa/Line P surveys) and colonies sites, to make this assessment. Seabird timing of breeding, productivity, and abundance at sea have changed in ways consistent with predictions under an ocean-warming scenario, but we cannot dismiss the hypothesis that low-frequency variability explains some of these patterns. In contrast, recent reproductive failures of auklets and other species cannot be explained by El Niño-Southern Oscillation (ENSO) or low-frequency variability. Declining trends in the productivity of murre and auklet "trophic chains," including the relative abundance of mesozooplankton (krill) and forage fish (juvenile *Sebastes*) cannot be explained by low- or high- (ENSO-scale) frequency climate variability. Changes in relative abundance at sea in the CalCOFI and Line P study areas, however, could be related to change points related to regime shifts in the North Pacific Ocean. Contrasting trends in life history (timing), demographic (productivity), and population (density) patterns by species highlight the need to consider spatial ecology and habitat quality (food web attributes) in order to develop a deeper understanding of how climate change–ecosystem change is affecting seabirds in the CCE and adjacent North Pacific regions.

INTRODUCTION

Ocean warming is evident in the global ocean (Levitus et al. 2000), but the ecological consequences have been poorly documented, specifically in International Panel on Climate Change (IPCC) assessment reports (Richardson and Poloczanska 2008). Relative to many of the world's oceans, the California Current ecosystem (CCE) has been well-studied for a long period of time, and has been identified as a system with strongly coupled environmental and ecosystem variability. This variability occurs on multiple time scales from seasons to centuries (Hickey 1979; Bograd and Lynn 2003; Chavez et al. 2003; Field et al. 2006a, b).

The CCE is a complex ecosystem. In the south, the ecosystem is composed mostly of species with sub-tropical zoogeographical affinities, whereas sub-arctic species dominate in the north. There is substantial intra-annual variability in ecosystem dynamics, with seasonal pulses in productivity along a latitudinal gradient from south to north (generally earlier in the south, later in the north). Productivity is related to upwelling and other oceanographic processes that mix the water column and bring nutrients to surface waters to stimulate primary productivity (Hickey 1979). As a productive marine ecosystem, there are both well-developed commercial fishery and ecotourism (whale and seabird-watching) industries in all regions, resulting in significant public support for a healthy and robust ecosystem. Understanding current and future effects of climate variability and climate change on the CCE is therefore of great interest to the people of western North America.

The CCE responds to interannual climate variability, exemplified by El Niño-Southern Oscillation (ENSO) events (Lenarz et al. 1995), and long-term (interdecadal) variability exemplified by the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) and North Pacific Gyre Oscillation (NPGO, Di Lorenzo et al. 2008). Some secular trends in oceanographic processes have also been described (Rykaczewski and Checkley 2008). While the periodicity of ENSO events is relatively well-known, every three to seven years, the periodicity of the PDO/NPGO is poorly understood with only a few cycles evident in the longest available observational or modeled datasets. There is evidence that the periodicity and amplitude of various modes of climate variability is changing. For example, warm-water ENSO events in the North Pacific Ocean appear to have increased, with concomitant changes in marine ecosystem structure and functions (Hayward 1997; McGowan et al. 1998; Gergis and Fowler 2009). These changes are poorly understood mechanistically, both in the physical and biological realms. The lack of understanding of the interactions and relationships between various scales of temporal environmental variability, from seasonal to interannual to interdecadal, presents major complications for understanding the effect of long-term climate change on the CCE and related North Pacific large marine ecosystems. Specifically, change in the periodicity of interannual and/or interdecadal climate variability makes it difficult to assign effects of secular (unidirectional) climate change vs. natural (cyclical) variation to ecosystem dynamics. Natural variability may exacerbate or dampen signals of secular climate change depending on whether the natural variability is leading to warmer or cooler alternative stable states.

The complexity of the issue may be better understood by considering how key biological communities have changed and are changing in marine ecosystems. Plankton and seabirds have been put forth as reliable indicators of change in marine ecosystems (Cairns 1987; Beaugrand 2005; McGowan et al. 1996; Piatt et al. 2007; Lavaniegos and Ohman 2007). Both zooplankton and seabirds are well-known in the CCE, with documented changes in species composition, abundance, ecology, and distributions. Relative to ocean climate, zooplankton are: (1) ectothermic, making their physiology directly sensitive to changes in ocean temperature and ocean chemistry, (2) lower in the trophic web, suggesting a more direct link to primary production and effects on growth and reproduction, and (3) passive drifters in the ocean realm, such that changes in distribution must reflect changes in currents and/or water mass distributions. Some have argued that zooplankton are the most reliable indicators of system state (Richardson 2008). On the other hand, seabirds are endothermic, have a higher trophic level, and move rapidly from place to place on scales of hours and tens of kms in search of favorable habitat and prey fields. Such characteristics would appear to make them less reliable indicators of ecosystem change, but seabirds are arguably the most conspicuous of all marine organisms, and as upper-trophic level species, may "amplify" changes in physical oceanographic attributes and difficult-to-study mid-trophic level species, thereby providing meaningful signals of change (Sydeman et al. 2001; Taylor et al. 2002; Abraham and Sydeman 2004; Sydeman et al. 2006; Piatt et al. 2007). Seabirds congregate at colonies and at pelagic or nearshore ocean productivity "hotspots" where they can be studied in large numbers, providing for robust sample sizes.

In this paper, we examine oceanographic climate and ecosystem change by considering select case histories for seabirds in the CCE and the transition zone between the CCE and Gulf of Alaska (GoA) large marine ecosystems (from ~30°–52°N). We investigate how seabird population parameters (e.g., productivity), food habits, and community composition have changed over time, particularly from the early 1970s through 2007, where possible. This is the extent of the longest time series available for consideration, and untangling climate-predator-prey relationships is still a challenge. Specifically, we consider whether the observed changes in seabird parameters mostly reflect natural climate variability or a response to secular climate change, which we call "cyclic or episodic variability" or "trends," respectively. We also examine the hypothesis that change in seabird parameters can be related to changes in their forage base, a "bottom-up" perspective (Ware and Thompson 2005). To accomplish this goal for some time series, we examine relationships between seabird population parameters, oceanographic indices, and indices of prey abundance. Finally, because they are indicator species (Piatt et al. 2007), understanding seabird responses to climate variability and climate change may be important to understanding climate-forced ecosystem dynamics and predator-prey relationships for other upper-trophic level predators in the CCE which are inherently more difficult to study (e.g., fish), yet are of considerable economic and societal value. We surmise that as seabirds and some fish and marine mammals exist on similar trophic levels and consume similar prey, we can learn something about these more difficult-to-study organisms by developing a better understanding of climate-ecosystem-seabird interactions (Roth et al. 2007; Sydeman et al. 2008).

METHODS

The observational data we review and present herein have been collected over the past 40 years as part of long-term fisheries oceanography and seabird monitoring programs designed to inform management of CCE living marine resources (fig. 1). Information on seabird distribution and abundance at sea off southern California has been collected since May 1987 as part of the California Cooperative Oceanic Fisheries Investigation (CalCOFI; http://www.calcofi.net). This seabird program, initiated by R. R. Veit and J. A. McGowan, with funding from the National Science Foundation, has resulted in counts and density (no. birds/km^2) estimates of ~60 species of seabirds over the period (Veit et al. 1996; Hyrenbach and Veit 2003; Yen et al. 2006). Briefly, on CalCOFI surveys seabirds are counted using the 300 m strip transect method of Tasker et al. 1984. Details of observational

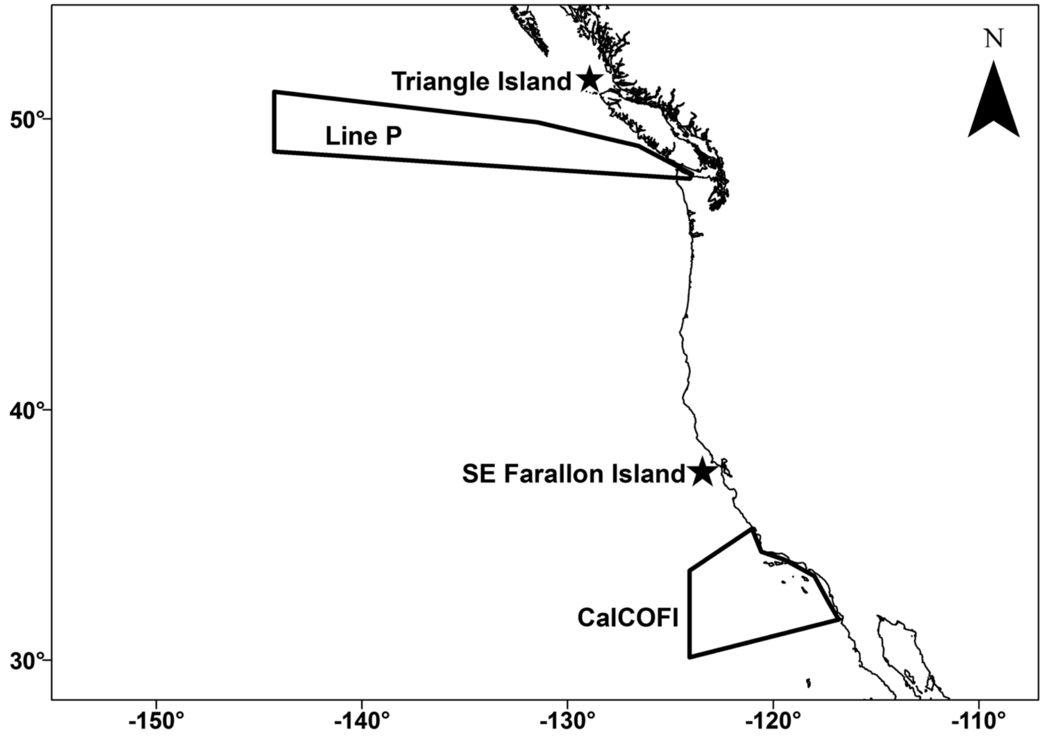


Figure 1. Map of the California Current Ecosystem (CCE) showing the locations of study areas referenced in this paper. The areal extent of the CalCOFI and Line P surveys are shown as polygons. Stars mark the locations of the Southeast Farallon Island and Triangle Island seabird colonies.

methods are available in the above papers. In this paper, we analyzed changes in the relative abundance of the overall seabird community as well as changes in two species/groups, "dark" shearwaters (mostly reflecting sooty shearwater, *Puffinus griseus*) and Cassin's auklet (*Ptychoramphus aleuticus*). We selected these species and those listed below from colonies because they are some of the most abundant seabird species in the system (Briggs et al. 1987), and they have been the subject of many previous studies.

The Canadian Department of Fisheries and Oceans (DFO), Station Papa Line P survey (http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/linepdata/default_e.htm) is situated in the transition zone between the CCE and the Gulf of Alaska ecosystem. The Line P transect is located in the CCE when the North Pacific Current traverses the North Pacific Ocean in a more northerly position, and is partly in the CCE and GoA when the current is distributed further south (Batten and Freeland 2007). Information collected on seabird distribution and abundance at sea in the GoA has been obtained since May 1996. This program, initiated by K. H. Morgan with funding from Environment Canada/Canadian Wildlife Service, has resulted in density (no. birds/km^2) estimates of ~40 species of seabirds over the period. Observational and analytical methods for this data set are available from Yen et al. 2005 and O'Hara et al. 2006. Given the relatively short length of this time series, there have been no previous attempts at trend analyses. In this paper, we examine overall changes in seabird abundance and diversity from 1996 through 2006, stratified by the season of observation (winter = February, summer = June, or fall = September).

Seabirds have been studied on numerous colonies in the CCE. Herein, we focus on results obtained at two, Southeast Farallon Island (SEFI) and Triangle Islands (TRI). SEFI is located in central-northern California (37°42'N, 123°00'W) in the heart of the Gulf of the Farallones National Marine Sanctuary and in a region downstream from one of the most dynamic upwelling cells (the Point Arena-Point Reyes cell) along the West Coast (Hickey 1979). SEFI is part of the Farallon National Wildlife Refuge operated by U.S. Fish and Wildlife Service. Monitoring of seabird populations on SEFI is conducted under a cooperative agreement with PRBO Conservation Science (formerly Point Reyes Bird Observatory). Overall design of the program may be attributed to D. G. Ainley who initiated many of the protocols still used today starting in 1971. Information collected for the Refuge includes estimates of population size, demographic and life history (e.g., timing of breeding) attributes, and food habits. Field and various analytical methods may be found in Ainley et al. 1995, Sydeman et al. 2001, and many of the references cited below. Previous trend analyses relative to long-term climate-ecosystem change include Sydeman et al. 2001, and relative to short-term climate anomalies include Sydeman et al. 2006 and Jahncke et al. 2008. In this paper, we examine estimates of annual breeding success and timing of breeding for trends.

TRI, like Line P, is located in the transition domain between the CCE and GoA. In general, unlike the role of upwelling in central-northern California, the mechanisms driving ocean productivity in this region are not well known. TRI is protected as the Anne Vallée Triangle Island Ecological Reserve (http://www.env.gov.bc.ca/bcparks/eco_reserve/anne_er.html). Monitoring of seabird populations there is conducted by Environment Canada-Canadian Wildlife Service and Simon Fraser University under a permit from the province of British Columbia. Overall design of the program may be attributed to K. Vermeer, who initiated studies on TRI in the mid 1970s, and I. Jones, who reinitiated the program in the early 1990s. Basic information collected includes indices of population size, demographic attributes, and food habits. Field and various analytical methods may be found in Bertram et al. 2001 and Hedd et al. 2006. We examine this data for trends in breeding success and relationships to oceanographic conditions.

Data Treatment and Statistical Analyses—Seabirds at Sea

For CalCOFI data, bird counts were summarized into "bins," generally 3 km in length. Survey densities were calculated by averaging the densities for all birds, "dark" shearwaters, and Cassin's auklets in all bins. For Line P data, bird counts were summarized per day, and then divided by the total area surveyed each day. Daily density estimates were averaged to produce survey estimates. Owing to the migratory nature of seabirds in the CCE and variation in the seasonal cycle of ocean productivity, we examined seasonal surveys separately (using Spearman rank correlation), or using a GLM approach (i.e., ANCOVA) that included "season" as a term, with "year" treated as a linear co-variate (i.e., df = 1) to test for trends. To approximate normality, survey-specific density estimates were log-transformed prior to all analyses. Surveys in the winter (January–February), summer (June–July), and fall (September–November) were used to examine trends and contrast patterns of change between CalCOFI and Line P for total bird density and species richness (fig. 2). There were no springtime (March–April) Line P surveys, hence the CalCOFI spring survey data were used only for investigating trends in shearwater and auklet densities and their relationships to ocean temperature (fig. 3). For illustrations, seasonal densities were expressed as anomaly statistics. To calculate anomalies in density, replicate surveys conducted in each season were averaged to produce a grand seasonal mean for each series (CalCOFI: 1987–2004; Line P: 1996–2006). Seasonal deviations (or anomalies) from the grand mean were calculated by subtracting the seasonal value for each year from the seasonal grand mean. To examine changes in dark shearwater and Cassin's auklet abundances relative to ocean temperature, we used CTD measurements at 100 m from line 80 in the CalCOFI grid (fig. 1); this line is located in the center of the CalCOFI study area; shearwaters were found over the entire study area (Yen et al. 2006) and for this species at least, line 80 provides a reasonable central location to investigate temperature relationships. Cassin's auklets were found mostly in the northern sector of the grid. Information from 1987 through 2004 is provided in this update. A more comprehensive analysis of species-specific trends, but for a more limited time period (1987–97) is available in Hyrenbach and Veit 2003.

Data Treatment and Statistical Analyses—Seabirds on Colonies

Data on timing of breeding, reproductive success and food habits (take of juvenile rockfish by murres) was analyzed using Spearman rank correlation to test for trends. For illustration, anomalies were calculated by subtracting annual means from a grand mean established for the entire time series for each species and parameter. Anomalies for seabird density, species richness, reproductive success, timing of egg-laying, and food habits are shown as histograms, with the 0-line reflecting the grand

TABLE 1
Trends in seabird species richness and density stratified by season for CalCOFI and Line P surveys. Spearman rank correlations, sample size and *p*-values for the above datasets.

	Winter			Summer			Fall		
Dataset	*N*	Spearman rho	$p < \|t\|$	*N*	Spearman rho	$p < \|t\|$	*N*	Spearman rho	$p < \|t\|$
CalCOFI Density	13	–0.3571	0.2309	**15**	**–0.5143**	**0.0498**	18	–0.4448	0.0644
CalCOFI Richness	13	–0.4635	0.1107	15	–0.4816	0.0691	**18**	**–0.6211**	**0.0059**
Line P Density	10	0.0667	0.8548	10	0.4182	0.2291	**8**	**0.7143**	**0.0465**
Line P Richness	**10**	**0.6342**	**0.0489**	10	–0.0675	0.853	**8**	**0.8982**	**0.0024**

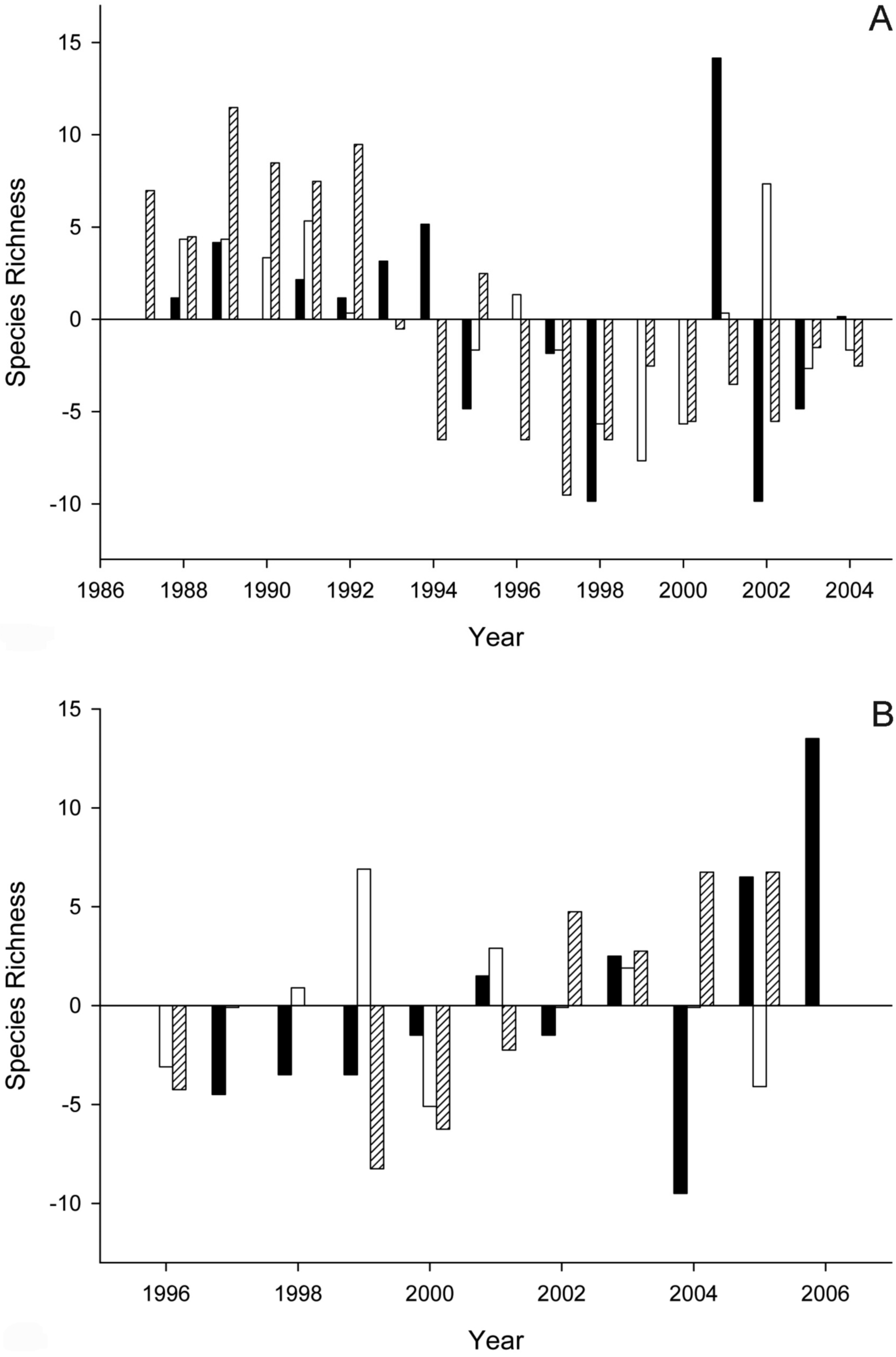
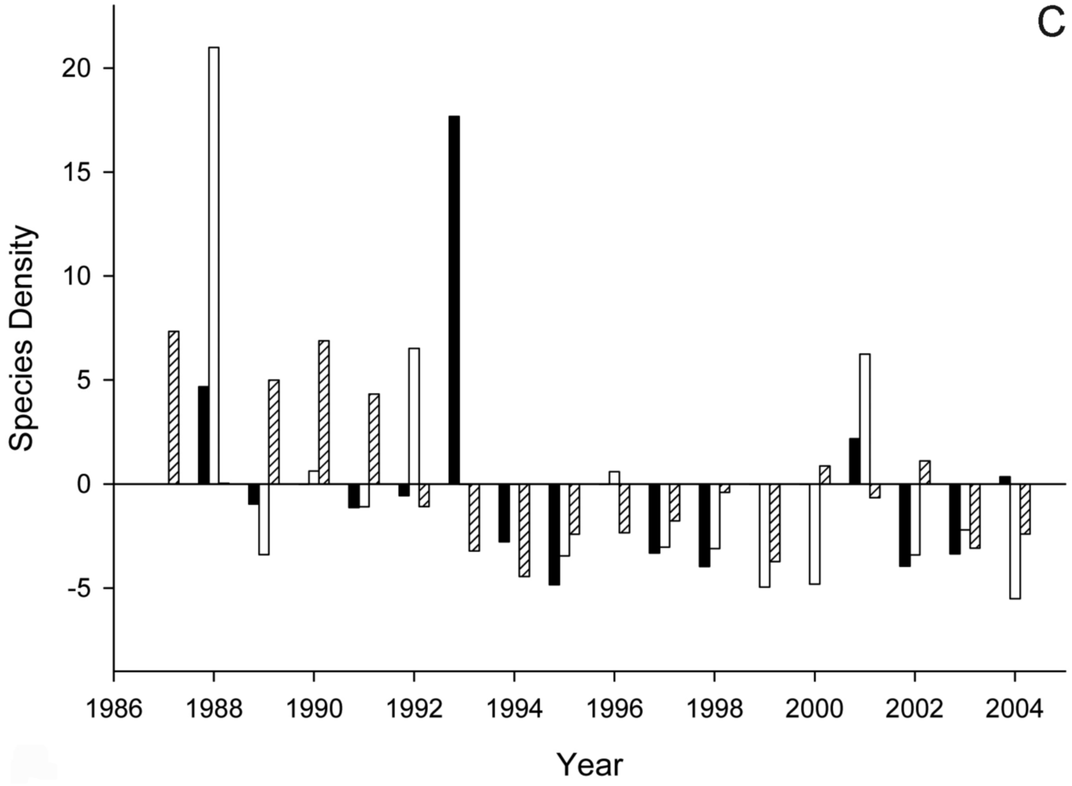


Figure 2. Trends in seabird species richness (seasonal anomalies, see text for details of calculations) and total seabird density (birds/km^2) from winter, summer, and fall long-term surveys in the southern and northern portions of the California Current Ecosystem. (A) CalCOFI species richness, (B) Line P species richness, (C) CalCOFI density.



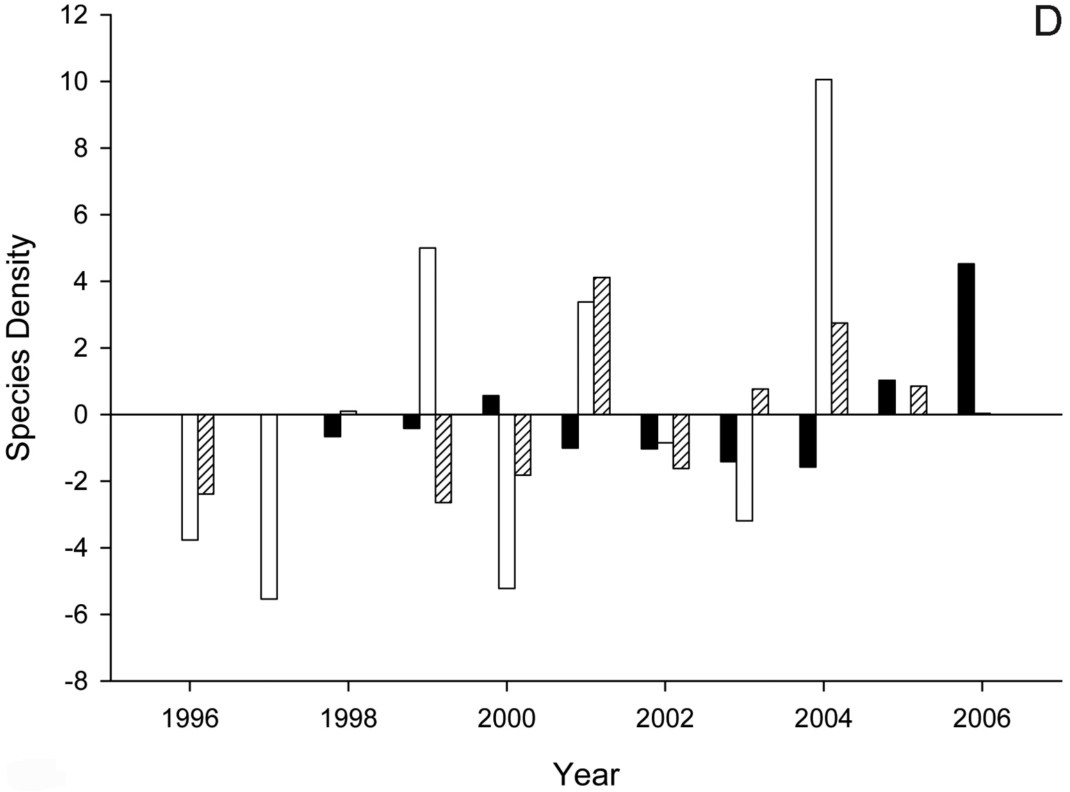


Figure 2. (continued) Trends in seabird species richness (seasonal anomalies, see text for details of calculations) and total seabird density (birds/km^2) from winter, summer, and fall long-term surveys in the southern and northern portions of the California Current Ecosystem. (C) CalCOFI density, (D) Line P density. Black bar = winter; open bars = summer, cross-hatched bars = fall.

seasonal (for densities) or annual (for other parameters) means. To illustrate years or seasons of substantial variation, we calculated the standard deviation of the anomalies; dashed lines above and below the 0-line in figures show 1 s.d. from the grand mean for each parameter.

RESULTS – CASE HISTORIES

Trends in Seabird Species Richness and Overall Abundance

Southern Trends from CalCOFI. Analysis of species richness (i.e., the number of individual species recorded on each survey), which provides a simple measure of community diversity, from winter, summer and fall CalCOFI surveys, reveals a general decline through time (tab. 1; fig. 2A), and with increasing temperature (ANCOVA: ln(species richness): overall F = 8.82, $p < 0.0001$, $R^2 = 0.4276$; season: F = 2.62, $p = 0.0594$; year: coefficient = –0.020, $F_{1,59} = 24.13$, $p < 0.0001$; temperature @ 100m on line 80: coefficient = –0.087, $F_{1,59} = 15.15$, $p = 0.0003$). Overall seabird density in the CalCOFI region also declined over time (Table 1; Figure 2c), and with increasing temperature (ANCOVA: ln(density): overall F = 6.58, $p = 0.0001$, $R^2 = 0.358$; season: F = 1.36, $p = 0.2651$; year: coefficient = –0.071, $F_{1,59} = 22.81$, $p < 0.0001$; temperature @ 100m on line 80: coefficient = –0.254, $F_{1,59} = 9.32$, $p = 0.0034$).

Northern Trends from Line P. In contrast to the CalCOFI data set, species richness on Line P increased through time (tab. 1; fig. 2B), though the time series (1996–2006) was considerably shorter. Analysis of change in species richness reveals seasonal variability and an increase in richness though time (ANCOVA: ln(species richness): overall F = 3.33, $p = 0.0364$, $R^2 = 0.2940$; season: $F_{2,24} = 2.49$, $p = 0.1036$; year: coefficient = 0.029, $F_{1,24} = 4.81$, $p = 0.0383$). The opposite pattern between CalCOFI and Line P is evident for seabird density as well. Analysis of density reveals seasonal variability and an increase though time (fig. 2D) (ANCOVA: ln(density): overall F = 7.00, $p = 0.0015$, $R^2 = 0.4667$; season: $F_{2,24} = 8.94$, $p = 0.0013$; year: coefficient = 0.103, $F_{1,24} = 5.32$, $P = 0.0300$).

Trends in Density, Timing and Productivity for Select Species

(1) Dark (Sooty) Shearwaters

Dark shearwaters are the most abundant species observed during CalCOFI surveys, particularly in the spring and summer (Hyrenbach and Veit 2003). Analysis of change in density reveals a decline though time, seasonal variability, but no effect of temperature (fig. 3A, C; ANCOVA: ln(density): $F_{6,58} = 14.02$, $p < 0.0001$, $R^2 = 0.543$; season: $F_{3,58} = 19.76$, $p < 0.0001$; year: coefficient = –0.045, $F_{1,58} = 14.01$, $p = 0.0004$; temperature @ 100m on line 80: coefficient = –0.037, $F_{1,58} = 0.30$, $p = 0.587$). While the decline in shearwater density previously reported (Veit et al. 1996; Hyrenbach and Veit 2003) is confirmed by this updated analysis, we were unable to distinguish whether the rate of decline has accelerated or leveled-off; in GLM, we fit different transformations of year, but none were any better than the linear model of decline (unpubl. data). Nonetheless, from the data alone it appears that the decline has leveled-off in recent years (fig. 3A).

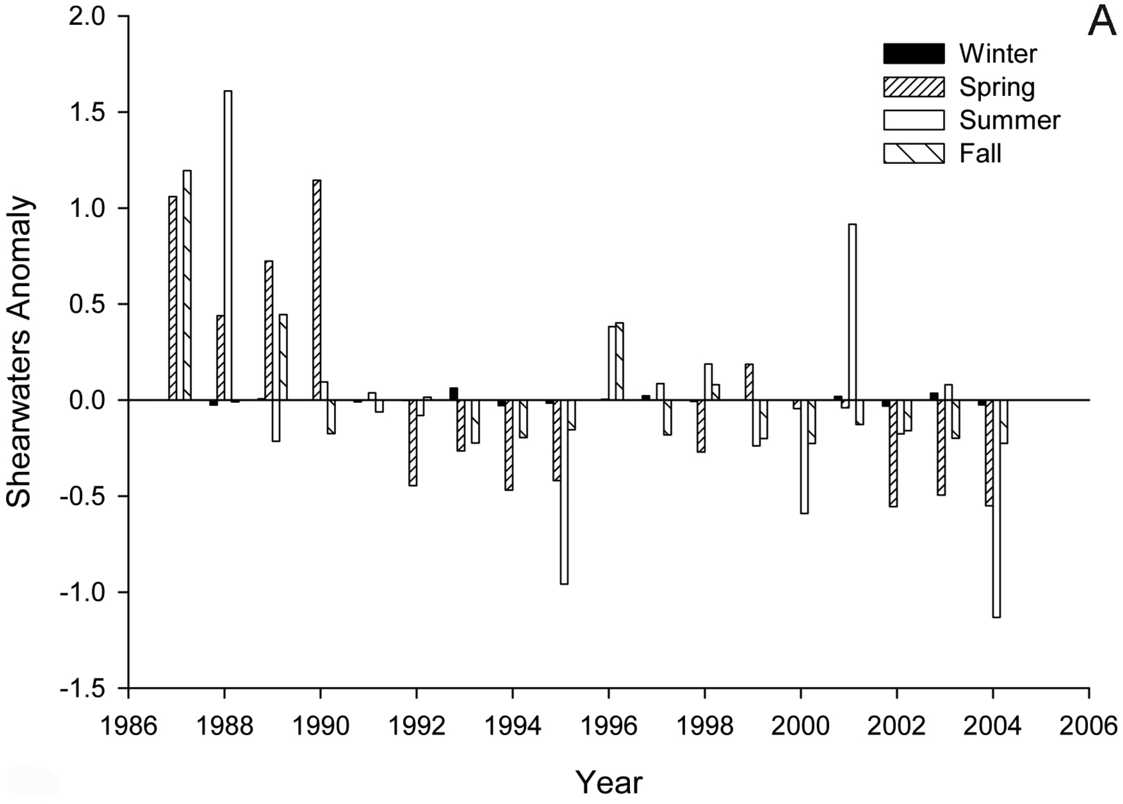
(2) Cassin's Auklet

Analysis of change in CalCOFI auklet density reveals a decline through time, seasonal variability, but no effect of temperature during the survey period (fig. 3B, D; ANCOVA: ln(density): F = 6.36, $p = 0.0001$, $R^2 = 0.3503$; season: F = 8.38, $p = 0.0001$; year: coefficient = –0.015, $F_{1,59} = 6.22$, $p = 0.0155$; temperature @ 100m on line 80: coefficient = –0.041, $F_{1,59} = 1.53$, $p = 0.2211$).

The timing of breeding and productivity of Cassin's auklet has been monitored on Southeast Farallon Island (SEFI) since 1972 (timing: mean egg-laying date) and 1971 (productivity: mean number of young fledged/pair/year), respectively. On the interannual scale, there is substantial variability in mean egg-laying dates (fig. 4A), with notable delays of 40–60 days in average timing during ENSO events that affected wintertime conditions (1983, 1992, 1998; see also Schroeder et al., in press). Recent auklet productivity failures in 2005–07 do not correspond to ENSO events (fig. 4B). While there are no significant trends in the mean values of either parameter, both timing and productivity have become significantly more variable through time (tab. 2). Moreover, despite a period of generally later breeding in the 1990s and earlier breeding thereafter, there is no significant

TABLE 2
Trends in means and variance in seabird timing of breeding and reproductive success (average number of offspring fledged/pair) over the past 35 years.

	N	Spearman rho	*p* < |t|
Means			
Cassin's Auklet Mean Egg Laying Date	35	0.2614	0.1293
Common Murre Mean Egg Laying Date	**35**	**–0.3263**	**0.0557**
Cassin's Auklet Reproductive Success	37	–0.0937	0.5810
Common Murre Reproductive Success	**36**	**–0.2910**	**0.0851**
Brandt's Cormorant Reproductive Success	**37**	**0.4692**	**0.0034**
Interdecadal Variance			
Cassin's Auklet Mean Egg Laying Date	4	0.4	0.6
Common Murre Mean Egg Laying Date	4	0.2	0.8
Cassin's Auklet Reproductive Success	**4**	**1**	**0**
Common Murre Reproductive Success	4	0.4	0.6
Brandt's Cormorant Reproductive Success	4	–0.2	0.8
PCA			
Community Productivity (PC1)	36	–0.0986	0.5673



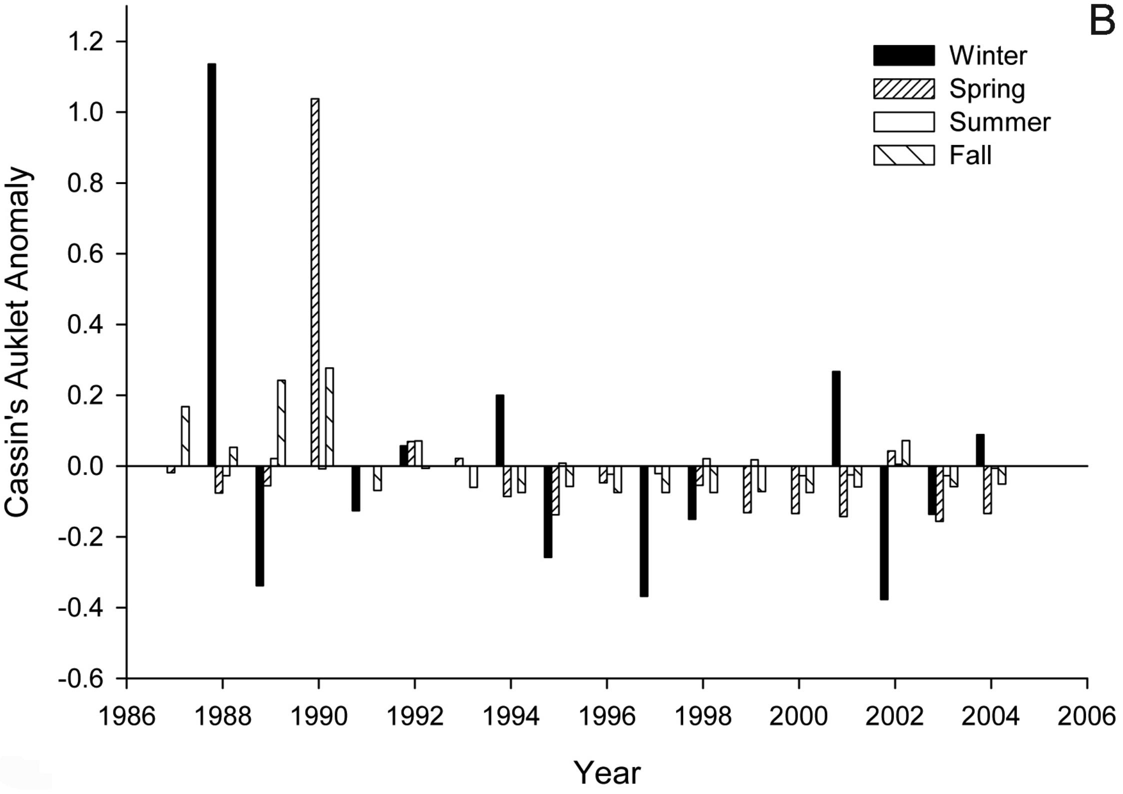


Figure 3. Trends in density (seasonal anomaly in birds/km^2) of (A) dark shearwaters (assumed to be mostly sooty, *Puffinus griseus*) and (B) Cassin's auklet (*Ptychoramphus aleuticus*) from long-term CalCOFI surveys. See text for statistical analyses and explanation of anomaly calculations.

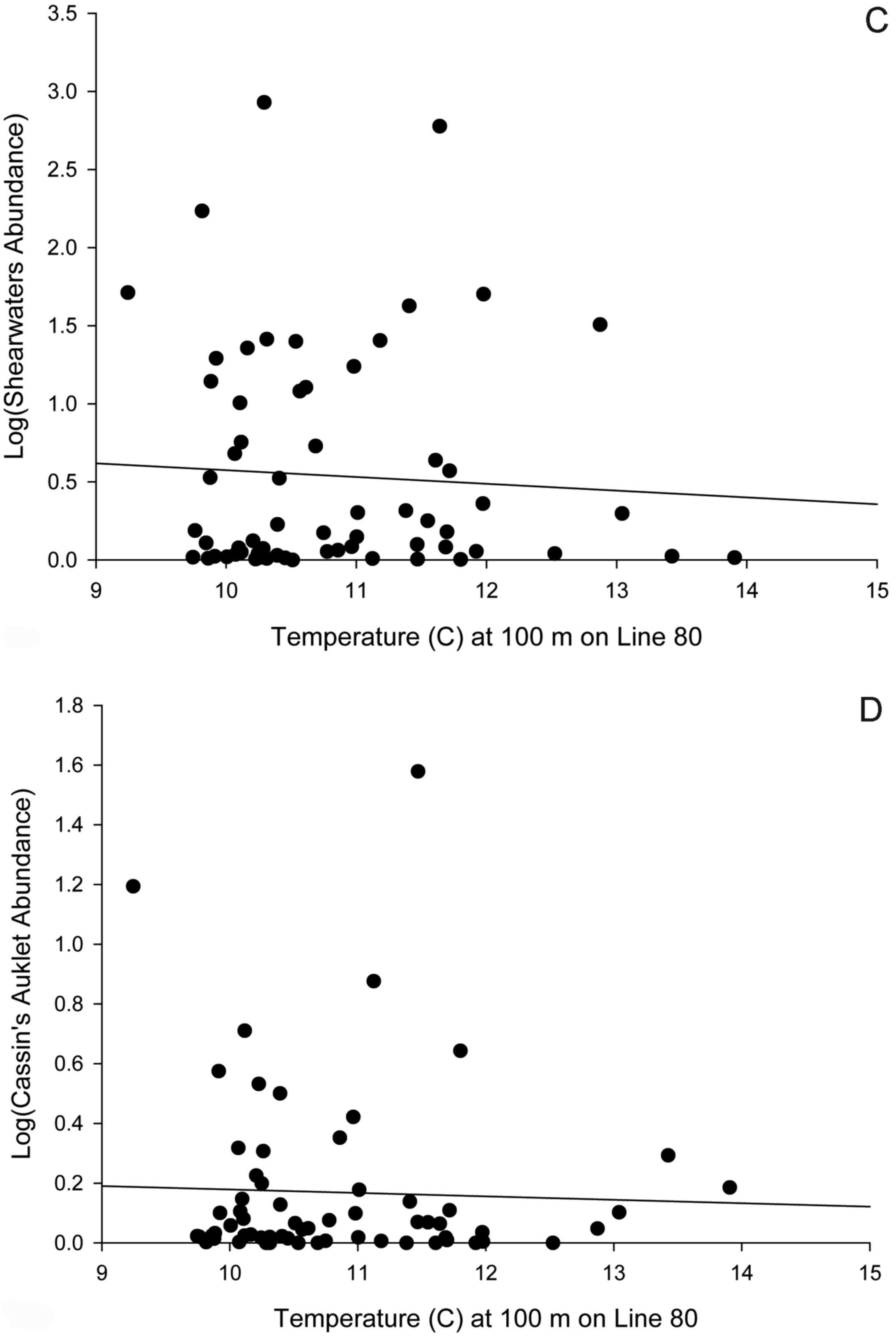


Figure 3. (continued) Scatterplots of the relationships between (C) dark shearwater density, and (D) auklet density relative to ocean temperature (mean T @ 100m on line 80) for surveys between May 1987 and November 2004. See text for statistical analyses and explanation of anomaly calculations.

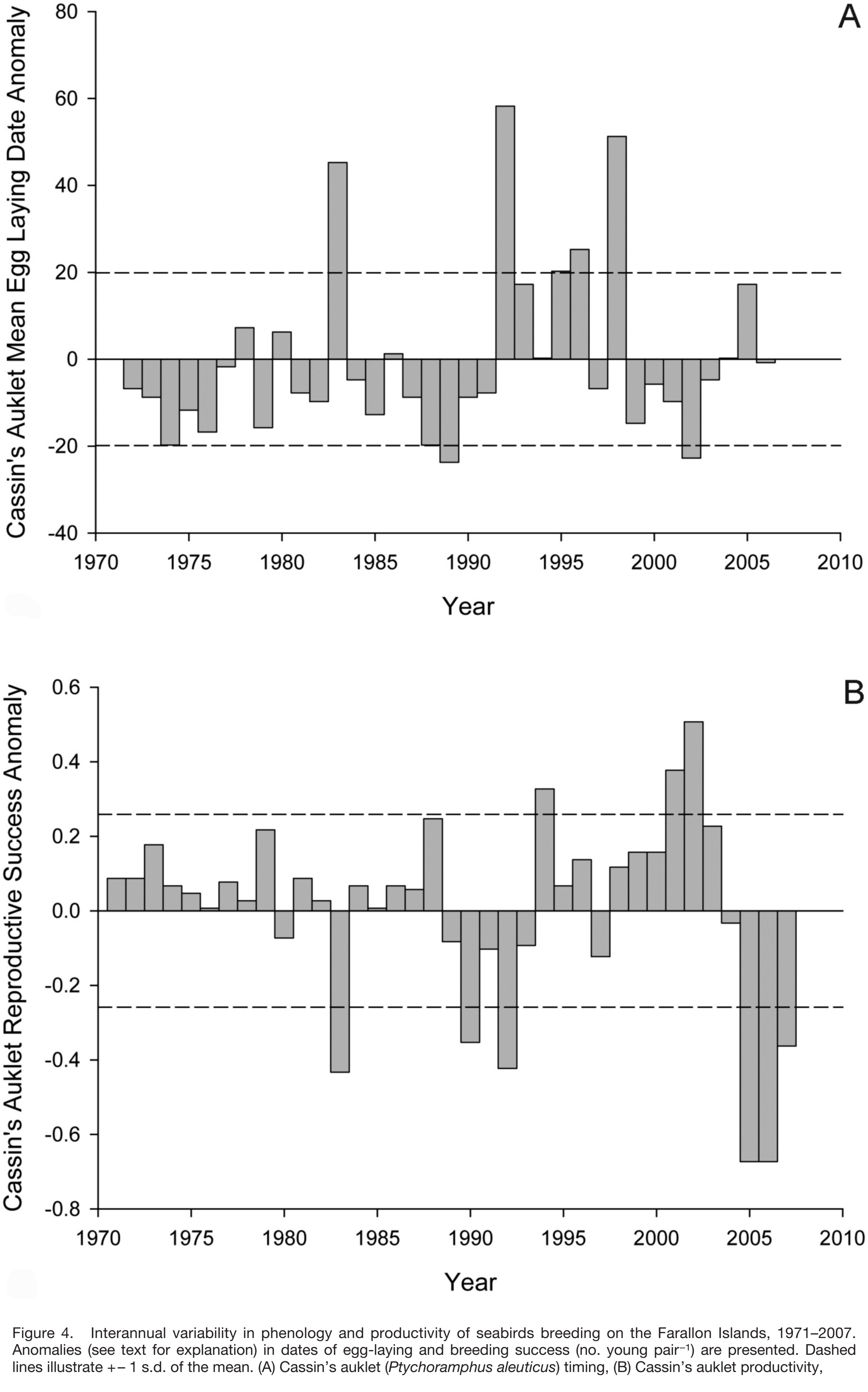
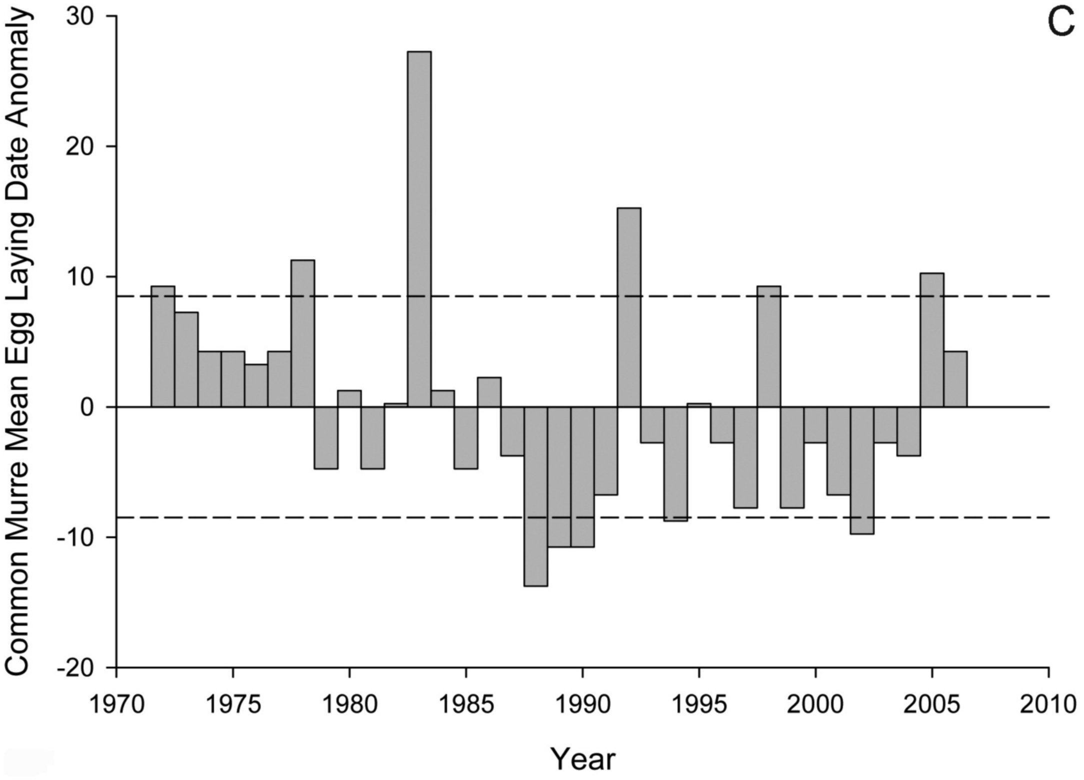


Figure 4. Interannual variability in phenology and productivity of seabirds breeding on the Farallon Islands, 1971–2007. Anomalies (see text for explanation) in dates of egg-laying and breeding success (no. young pair^{-1}) are presented. Dashed lines illustrate +– 1 s.d. of the mean. (A) Cassin's auklet (*Ptychoramphus aleuticus*) timing, (B) Cassin's auklet productivity,



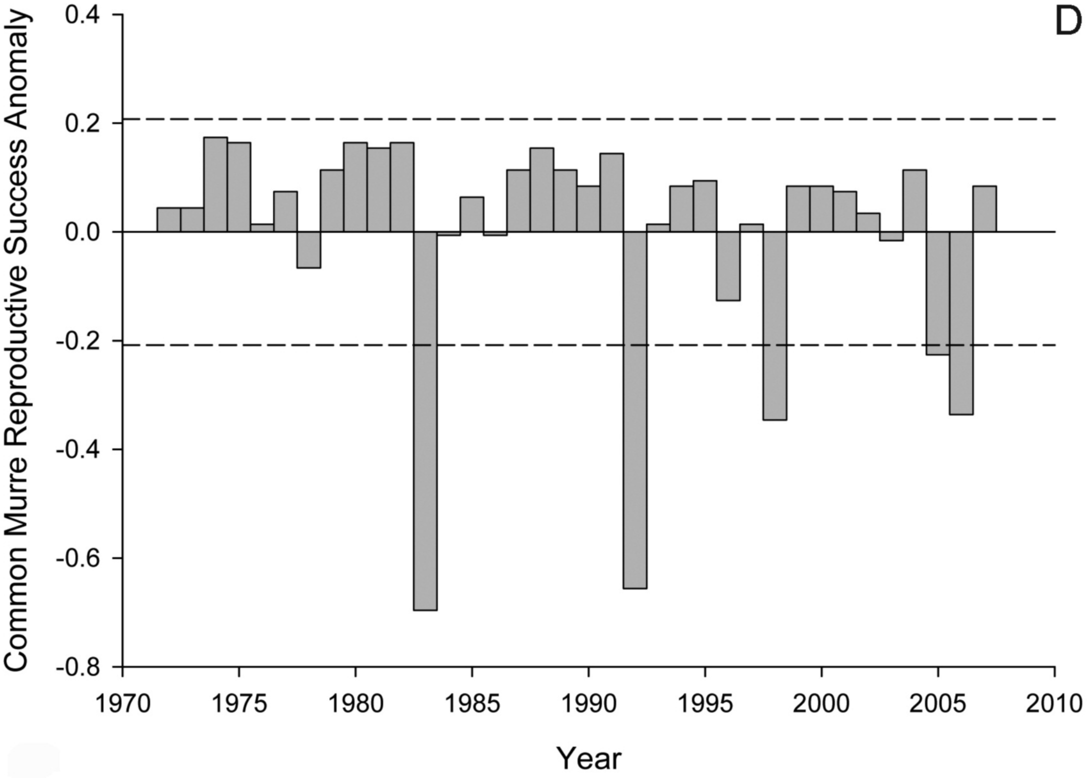


Figure 4. (continued) Interannual variability in phenology and productivity of seabirds breeding on the Farallon Islands, 1971–2007. Anomalies (see text for explanation) in dates of egg-laying and breeding success (no. young pair^{-1}) are presented. Dashed lines illustrate +– 1 s.d. of the mean. (C) common murre (*Uria aalge*) timing, (D) common murre productivity, (1972–2007).

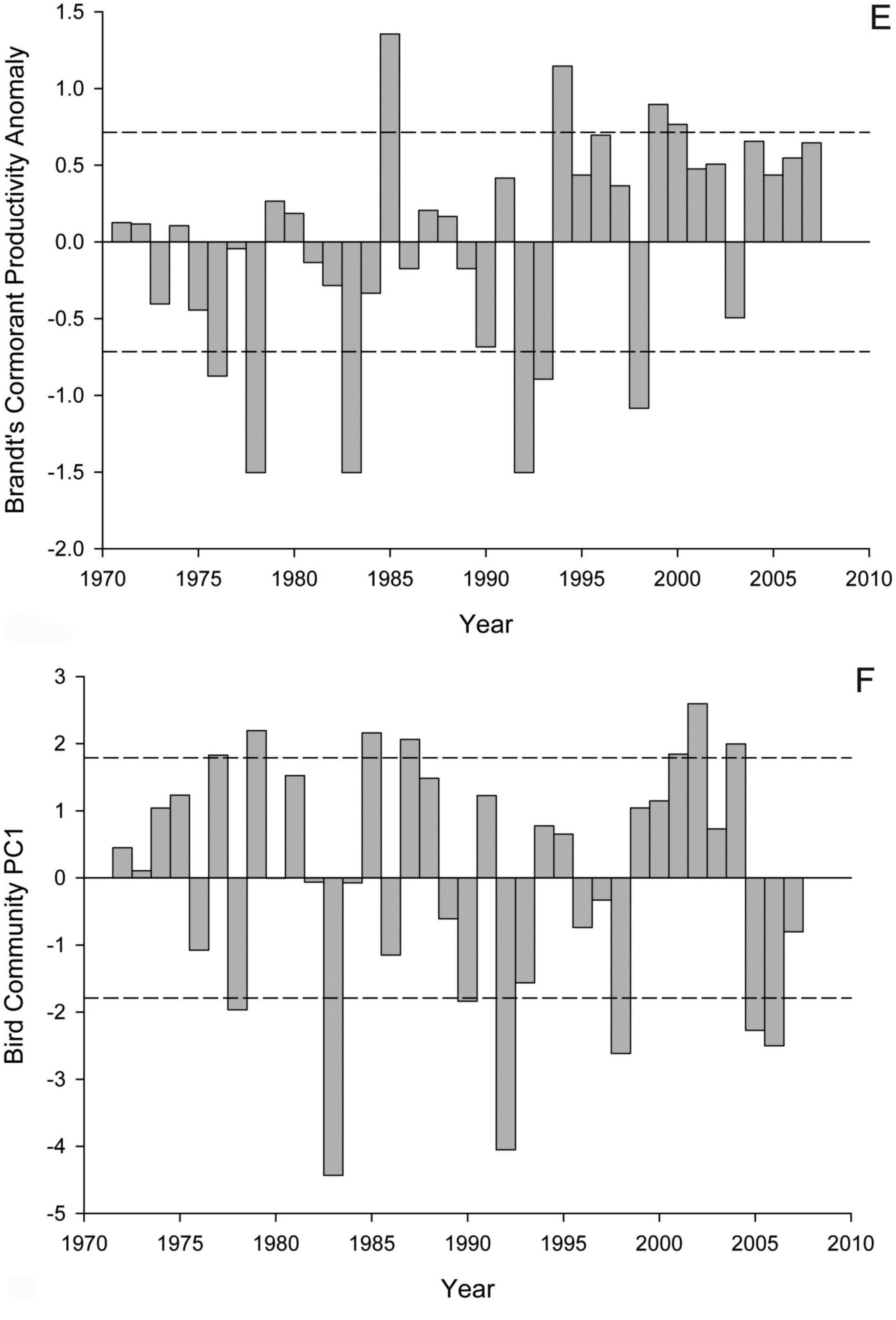


Figure 4. (continued) Interannual variability in phenology and productivity of seabirds breeding on the Farallon Islands, 1971–2007. Anomalies (see text for explanation) in dates of egg-laying and breeding success (no. young pair^{-1}) are presented. Dashed lines illustrate +− 1 s.d. of the mean. (E) Brandt's cormorant (*Phalacrocorax penicillatus*) productivity, and (F) community productivity assessed as PC1 of western gull (*Larus occidentalis*), Brandt's cormorant, common murre, pigeon guillemot (*Cepphus columba*), pelagic cormorant (*Phalacrocorax pelagicus*), and Cassin's auklet productivity (1972–2007).

TABLE 3

Cross-correlations (Spearman rank) of Cassin's auklet (*Ptychoramphus aleuticus*) reproductive success at the Farallon Islands, California (1971–2007), against monthly values for the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), Northern Oscillation Index (NOI), and Southern Oscillation Index (SOI). Bold, underlined indicates a significant correlation, $p < 0.05$. The auklet's breeding season lasts from approximately March–September each year. Atmospheric and oceanographic conditions prior to egg-laying may be important determinants of breeding success (no. young produced/pair/year), hence are included here.

	PDO		NPGO		NOI		SOI	
Month	Spearman rho	$p < \|t\|$	Spearman rho	$p < \|t\|$	Spearman rho	$p < \|t\|$	Spearman rho	$p < \|t\|$
January	0.1190	0.4828	0.2747	0.0999	0.0395	0.8164	0.1373	0.4176
February	0.0095	0.9555	0.2968	0.0745	0.1475	0.3836	0.2272	0.1763
March	0.0357	0.8338	0.3019	0.0694	0.1740	0.3031	0.1597	0.3451
April	–0.0836	0.6230	0.2999	0.0714	0.2216	0.1874	0.1719	0.3091
May	–0.2461	0.1420	**0.3852**	**0.0186**	0.0749	0.6596	–0.0134	0.9372
June	–0.3017	0.0696	**0.3706**	**0.0239**	0.1807	0.2844	0.1722	0.3081
July	**–0.4197**	**0.0097**	**0.3409**	**0.0389**	0.1967	0.2431	0.2607	0.1191
August	**–0.3917**	**0.0165**	0.3136	0.0587	0.1625	0.3367	0.1983	0.2395
September	**–0.3583**	**0.0295**	0.3119	0.0602	–0.1881	0.2649	0.2004	0.2343

non-linear trend in the auklet's timing of breeding ($F_{2,32} = 1.35, p = 0.274$).

Over the entire time series, 1971–2007, cross-correlations of auklet productivity against monthly large-scale climate indices reveal significant relationships with monthly values of the NPGO in May–July, and PDO in July–September (tab. 3). Notably, unlike the other indices, all of the correlations with the NPGO were consistent in sign from January through September. We found no correlation with monthly values of the Northern Oscillation Index or Southern Oscillation Index. The most compelling correlations involve the NPGO as it overlaps most in time with the auklet's breeding season.

In the northern CCE, the timing of breeding, reproductive success, mass of offspring at fledging (independence), and food habits of Cassin's auklets and rhinoceros auklets (*Cerorhinca monocerata*) have been monitored continuously since 1996. Cassin's auklets at Triangle Island are a significant indicator of the timing of annual mesozooplankton biomass peaks, but in this case a single calanoid copepod, *Neocalanus cristatus,* is a primary component of nestling diets and the key determinant of productivity (Bertram et al. 2001; Hipfner, in press). Wolf et al. 2009 compare the relationships between TRI and SEFI auklet timing of breeding and productivity with local and large-scale oceanographic variables during the years 2000–05, including SST, sea surface height (SSH), and upwelling indices in the auklet's foraging habitat during the breeding season. At both TRI and SEFI, auklets bred later when local SSH was higher, which indicates greater heat content (fig. 5A). At both TRI and SEFI, auklets also produced fewer offspring in years of higher SSH (fig. 5B). Notably, although the diets of these populations are different (mostly euphausiids in California, mostly copepods in British Columbia), auklets from these populations, spaced ~1300 km apart, responded similarly

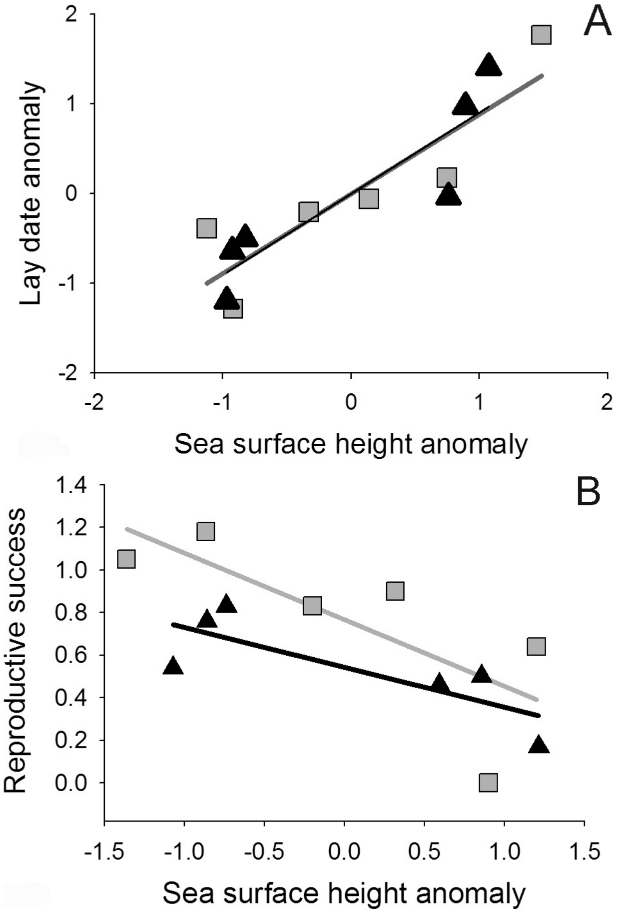


Figure 5. Relationships between (A) the annual mean lay date anomaly and sea surface height anomaly during the laying period and (B) productivity (chicks fledged per pair) and sea surface height anomaly (during the breeding period) for Cassin's auklets (*Ptychoramphus aleuticus*), with Triangle Island depicted as black triangles and Farallon Island depicted as grey squares. Figure modified from Wolf et al. 2009. For laying date on Farallones: $\beta = 0.89$, $t = 3.83$, $p = 0.019$, $r^2 = 0.79$. For laying date on Triangle: $\beta = 0.90$, $t = 4.16$, $p = 0.014$, $r^2 = 0.81$. For breeding success on Farallones: $\beta = -0.31$, $t = -2.23$, $p = 0.09$, $r^2 = 0.55$. For breeding success on Triangle: $\beta = -0.18$, $t = -2.61$, $p = 0.06$, $r^2 = 0.63$.

to oceanographic climate, highlighting how ocean climate may affect different populations similarly through varying, yet similar "bottom-up" mechanisms. Understanding the mechanisms underlying parallel or divergent demographic responses of widely-spaced populations foraging on different species is clearly an important area for future research.

(3) Common Murre

The timing of breeding and productivity of the Common murre (*Uria aalge*) has been monitored on SEFI since 1973. Farallon murres are a significant indicator for the abundance of forage fish, particularly juvenile rockfish in the region (Mills et al. 2007). On an interannual scale, there is substantial variability in egg-laying dates with delays of 15–25 days in average timing during severe ENSO events (1983, 1992, 1998); there was also substantially late breeding (i.e., >1 s.d. of the mean) in 2005 (fig. 4C). There have also been nearly complete murre productivity failures in 1983 and 1992, and substantially reduced production in 1998 and 2005–06 (fig. 4D). There is a negative trend in murre productivity and timing (despite the delays in 2005 and 2006), but in both cases the trend was weakly significant ($0.10 > p > 0.05$; Table 2). There is also no significant change in the variance in these parameters.

(4) Brandt's Cormorant

The productivity of Brandt's cormorants (*Phalacrocorax penicillatus*) has been monitored on SEFI since 1971. Farallon cormorants are a significant indicator for the abundance of forage fish, particularly juvenile rockfish and anchovies in the region (Nur and Sydeman 1999). On an interannual scale, cormorants show the same pattern of failures as murres and auklets, with complete productivity collapses in El Niño years, 1983 and 1992, and substantially reduced production in 1998; however, unlike the other species their reproductive success was within normal bounds in 2005 and 2006 (fig. 4E). Moreover, there has been a significant linear increase in productivity (tab. 2), as first reported by Sydeman et al. 2001 for the same time series, but ending in 1997. Ten years later, the pattern remains the same. As opposed to murres (no change in variance) and auklets (increasing variance), there is a non-significant decrease in the variance of cormorant productivity over the nearly four decades of study.

(5) Rhinoceros Auklet

Triangle Island rhinoceros auklets appear to be a significant indicator for the abundance of forage fish, particularly sandlance (Hedd et al. 2006). This time series is short, but on an interannual scale, rhinoceros auklets show a similar pattern of variability to Farallon murres and Cassin's auklets, with poor productivity in the late 1990s, reasonable success in 1999–2002, followed by a poor year in 2005 (fig. 6A). Fledgling mass follows the same interannual pattern of variability. There was no trend in this parameter through time (tab 4).

TABLE 4
Trends in the reproductive success and fledging mass of rhinoceros auklets (*Cerorhinca monocerata*) on Triangle Island.

	N	Spearman rho	$p < \lvert t \rvert$
Productivity	14	0.1364	0.6419
Fledgling Mass	14	0.1473	0.6154

TABLE 5
Trends in the take of rockfish by common murres (*Uria aalge*) and abundance in the environment.

	N	Spearman rho	$p < \lvert t \rvert$
Juvenile Rockfish	25	–0.4546	0.0224
Rockfish in Common Murre Diet	32	–0.581	0.0005

Trends in Community Metrics: Linking Seabird Productivity and Trophic Structure

(1) Multivariate Farallon Productivity Index

Sydeman et al. 2001 developed a multivariate index of seabird breeding success on the Farallones; Figure 4F is an update to the Sydeman et al. figure. The index is based on the three species discussed above, as well as the pelagic cormorant (*Phalacrocorax pelagicus*, PECO), pigeon guillemot (*Cepphus columba*, PIGU), and western gull (*Larus occidentalis*, WEGU). Productivity trends for these species indicate variability (PECO), a weak non-significant decline (PIGU) and a strong decline (WEGU; W. J. Sydeman, unpubl. data). When coupled, the six species reveal the same patterns of variability, with overall community failure in 1983, 1992, and 1998 (all below 1 s.d. of the mean), a period of reasonably high productivity from 1999–2003 (above 1 s.d. of the mean), and very poor productivity in 2005 and 2006 (below 1 s.d. of the mean). There is no trend in the mean or variance of community-wide productivity (tab. 2).

(2) The Importance of Juvenile Rockfish (*Sebastes* spp.)

The diets of Farallon common murre chicks have been monitored since 1973. The abundance of prey in the region, including juvenile rockfish, anchovies, and other forage fish, has been monitored since 1983 through NMFS trawl surveys (NMFS/S. Ralston, unpubl. data[1]). On a long-term scale, murre chick diets and NMFS trawl surveys show the same temporal pattern of collapse in juvenile rockfish relative abundance starting in ~1989–90 (Mills et al. 2007, fig. 7A). Murre chick diets show a slight recovery in the take of juvenile rockfish in 2001–04, matched to a lesser extent by the trawl surveys in the

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[1] S. Ralston, NOAA/NMFS/SWFSC, 110 Shaffer Road, Santa Cruz, California, 95060.

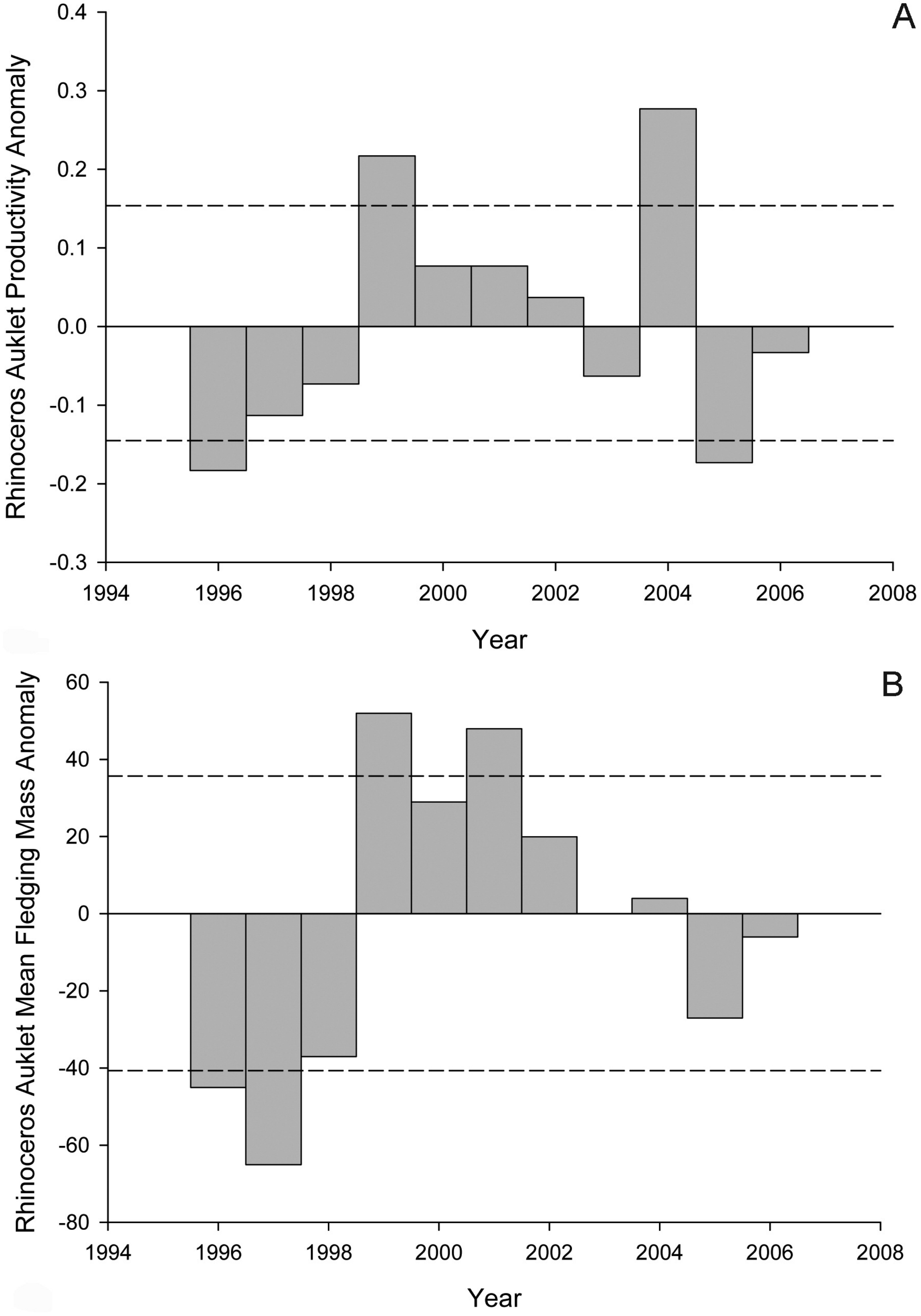

Figure 6. Interannual variability in (A) reproductive success and (B) mass of young at fledging for rhinoceros auklets (*Cerorhinca monocerata*) breeding on Triangle Island, British Columbia, 1996–2006. Anomalies (histogram) in productivity (no. young/pair) and fledging mass (G) are presented (see text for analytical details). Dashed lines illustrate +– 1 s.d. of the mean.

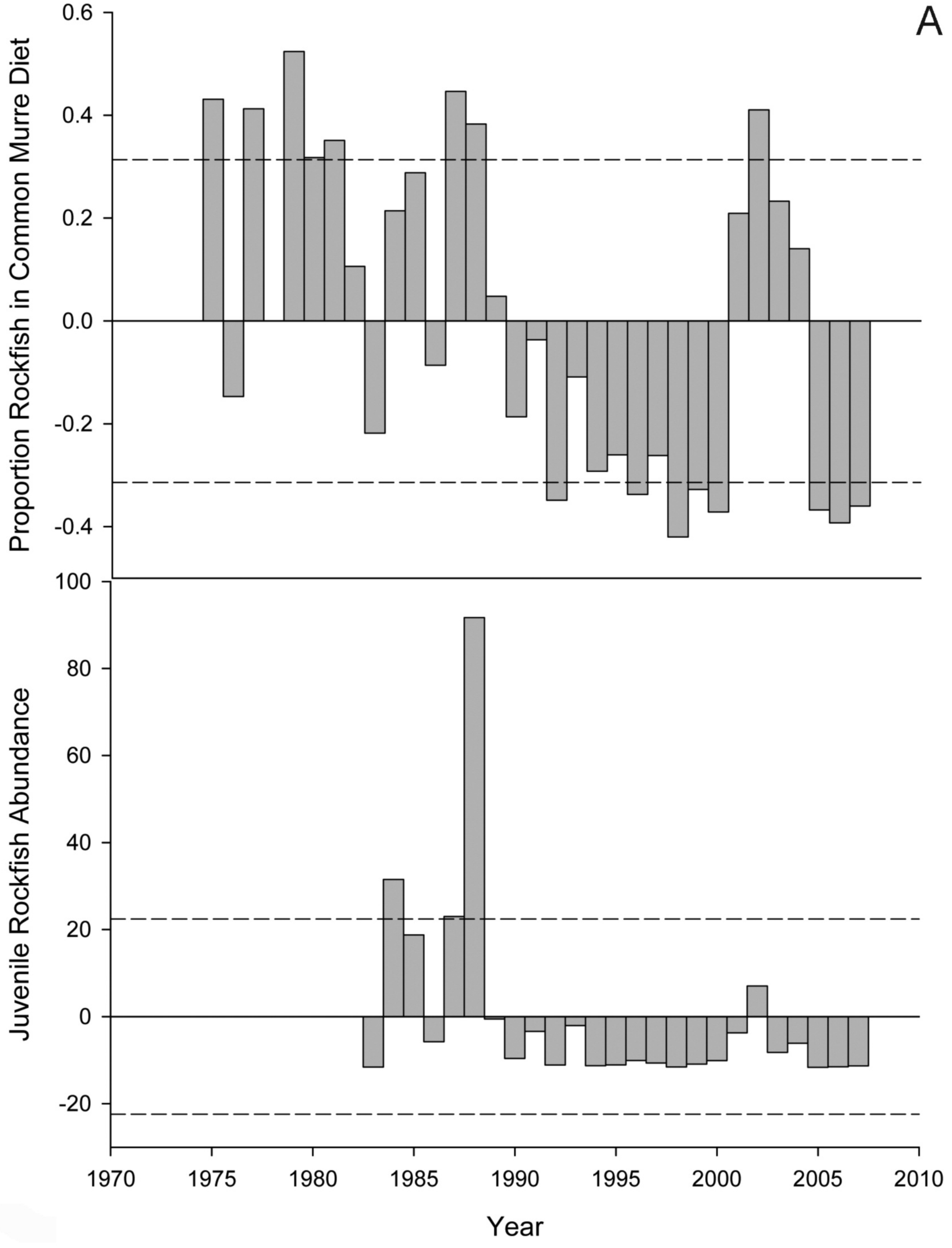

Figure 7. (a) Time series of interannual anomalies (see text for details of calculations) in the take of juvenile rockfish (*Sebastes* spp.) by common murres (*Uria aalge*) on the Farallon Islands (1975–2007) and the abundance of juvenile rockfish in the greater Gulf of the Farallones as measured by NOAA-NMFS (1983–2007; S. Ralston and J. Field, unpubl. Data[1]). Dashed lines illustrate +– 1 s.d. of the long-term mean.

same years (fig. 7A), followed by three years of no rockfish in the diet or trawls in 2005–07. There is a significant linear decrease in both of these indices of juvenile rockfish abundance (tab. 5). The relationship between juvenile rockfish in the murre's diet and relative abundance in the environment follows an exponential plateau curve (fig. 7B). At low and high levels of rockfish abundance, there was little change in the murre diet composition, but at moderate levels of prey abundance, there was a linear change in the murre's diet.

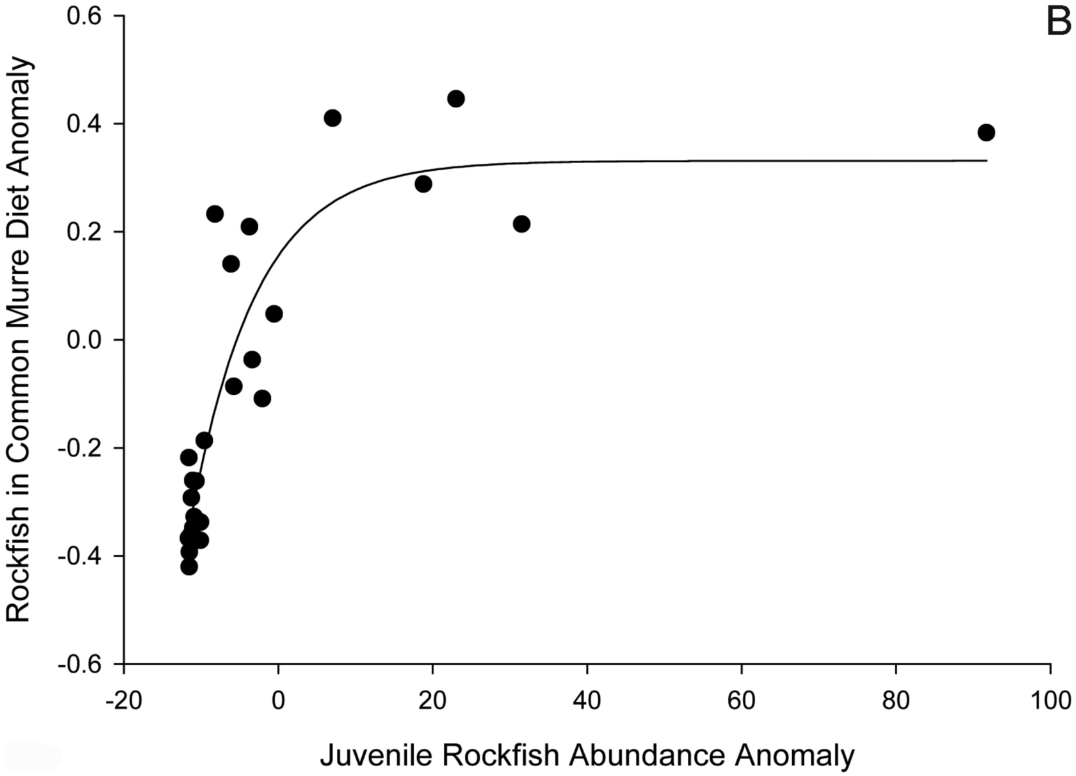

Figure 7. (continued) (b) The relationship between juvenile rockfish abundance in the environment as determined by NOAA-NMFS and take of juvenile rockfish by murres; fit is an exponential rise to maximum, 3 parameter GLM; $R^2 = 0.81$.

(3) Food Chains and Productivity

Wells et al. 2008 developed a multivariate index of murre and auklet food chains for the Gulf of the Farallones, combining seabird data with information on the abundance of prey from the NMFS juvenile rockfish survey, as well as mesozooplankton abundance from CalCOFI surveys. Using this multivariate index, we have determined that both the auklet trophic chain, comprised of mesozooplankton and auklets, and the murre trophic chain, comprised of mesozooplankton, juvenile rockfish, and murres, have become less productive through time. In both cases, there is a declining trend in productivity for these multivariate food web indicators (fig. 8A, B).

DISCUSSION

Parmesan 2006 reviewed the possibilities of ecological and evolutionary change in relation to climate change, focusing primarily on terrestrial biota, and suggested a few fundamental observations which may be evident in all ecosystems. These include: (i) change in the timing of biological events, (ii) change in the geographic range and/or relative abundance of species, (iii) change in the community structure, and (iv) change in population or "system" productivity. We found evidence for changes in seabird communities and population parameters in the CCE that are consistent with the possible responses to climate change: (i) mean egg-laying dates for one species (murres) became earlier through time (i.e., changes in timing); (ii) species mostly found in colder waters (i.e., shearwaters and auklets) became less abundant in the southern CCE, corroborating previous reports on these species (Veit et al. 1996; Oedekoven et al. 2001; Hyrenbach and Veit 2003) (i.e., changes in geographic range and abundance); (iii) the seabird community in the southern CCE had become less abundant and less diverse, while that of the northern CCE had become more abundant and more diverse (i.e., changes in community structure); and (iv) productivity of some species declined, whereas for others it increased (i.e., changes in productivity). In relation to changes in productivity, we demonstrate that changes in productivity for two species—auklets and murres—were related to changes in the abundance/availability of their prey (zooplankton and forage fish), and that when coupled, multivariate indices of productivity, integrating zooplankton, fish and birds, also declined (Wells et al. 2008). Finally, although Parmesan 2006 did not make generalizations about change in parameter variability (or variance), we found increasing variance in the productivity for one species (Cassin's auklet) at SEFI.

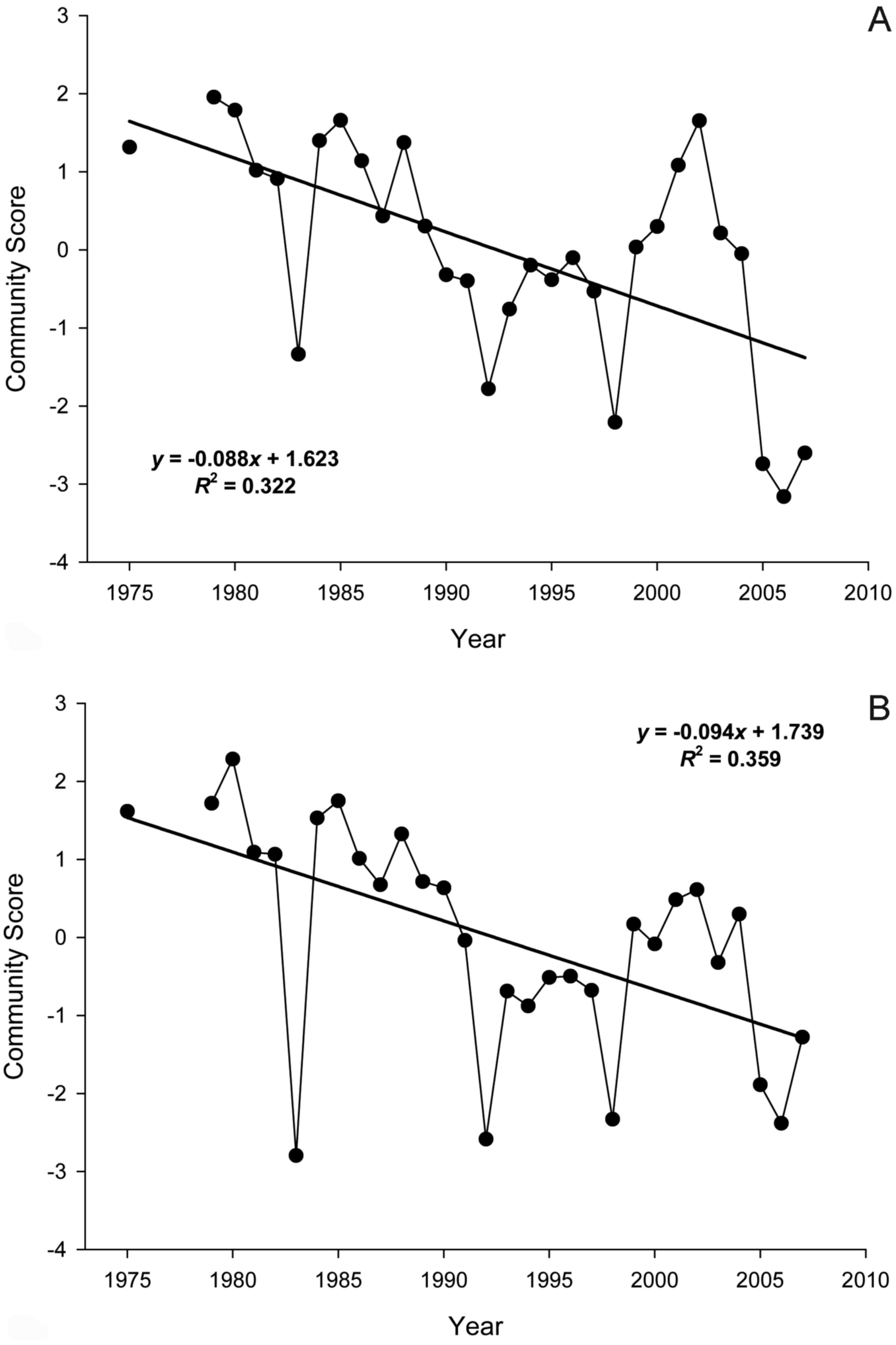

Figure 8. Trends in the multivariate "trophic chain" productivity for (A) Cassin's auklet (*Ptychoramphus aleuticus*) and (B) common murre (*Uria aalge*) in the Gulf of the Farallones, 1975, 1979–2008, as determined by Wells et al. 2008, updated to include 2007. Y axis reflects dimensionless units. Trophic chain for auklets includes measured and modeled "small zooplankton" from CalCOFI surveys in the region and auklet productivity. Trophic chain for murres includes measured and modeled "small zooplankton," estimated juvenile rockfish abundance from NMFS surveys in the region and murre productivity. See Wells et al. 2008 for statistical details.

Seabirds at Sea

We confirmed previous reports that in conjunction with ocean warming, seabirds with cold-water zoogeographic affinities have declined in the southern CCE (our fig. 2; Hyrenbach and Veit 2003). The decline in the numerically dominant shearwaters (fig. 3A), in particular, is associated with an overall decline in seabird community density in the southern CCE (fig. 2C). In contrast, seabird density along Line P increased, as did the richness of species encountered. While it is beyond the scope of this synthesis to review species-specific changes on Line P, it seems possible that there have been range expansions of some seabird species to the north. This is in keeping with the overall increase in seabird density observed along Line P, which is also consistent with predictions for response to climate change. Northward range expansions have also been observed for long-lived groundfish in the North Sea (Perry et al. 2005) and Bering Sea (Mueter and Litzow 2008).

Climate and Food

In this study, seabirds apparently responded to ocean climate change indirectly through spatial and temporal changes in prey base. We showed that in the central-northern region (SEFI), there was a simultaneous decline in juvenile *Sebastes* abundance and a non-linear take of juvenile *Sebastes* by murres (see also Sydeman et al. 2001; Mills et al. 2007). The decline in juvenile *Sebastes* compared to the birds may be related to range shifts or a reduction in productivity. Moreover, we have demonstrated a secular decline in the "trophic chains" of murre and auklet productivity, meaning that the productivity of the zooplankton (mostly krill) and forage fish (mostly juvenile *Sebastes*), leading to auklet and murre productivity, has also declined. Parsing out all the linkages between upwelling, advection, prey and predators is beyond the scope of this review, but it is clear from this and other work (Bertram et al. 2001; Mackas et al. 2007; Jahncke et al. 2008; Wells et al. 2008) that changes in basic oceanographic processes such as upwelling in the CCE could be driving changes in prey populations and distributions, which ultimately affect these seabirds. Seabirds require sufficient food resources prior to the breeding season for the production of eggs, and food relatively close to the colony when they are rearing offspring. Murres feed dependent offspring multiple times each day, and require food, in this case juvenile *Sebastes*, available close to the colony. Auklets forage for zooplanktonic prey with which to feed offspring at dusk and store multiple prey items in a throat-pouch, and then regurgitate prey for chicks when they return to the colony. Dependent offspring are typically fed once per night by each parent. While the auklets do not return to the breeding colony more than once per day, their foraging ambit is still restricted (~60 km from the islands). Therefore, in 2005 and 2006 when krill were in low abundance, part of the problem seemed to be that no large krill patches were found in proximity to the Farallones (Santora et al.[2]).

Seabirds and Oceanographic Indices

The typical approach to understanding marine biota and ecosystem responses to climate change has been to develop simple, empirical correlations with environmental parameters. With this approach, seabirds of the CCE have provided numerous results, many of which are considered in this synthesis. However, it is important to consider that (i) correlations often break down over time (Myers 1998; see Miller and Sydeman 2004 for an example using murres and rockfish in the CCE), and (ii) no matter how solid the correlation, they provide little understanding of the actual mechanism of response. We have described several simple empirical correlations using temperature and sea surface height (SSH), and the covariance in these relationships for seabirds at sea and on colonies in the southern (CalCOFI), central-northern (SEFI), and northern (Line P, TRI) sectors of the CCE. In the case of SSH, auklets at both colonies responded similarly, with later breeding dates and decreases in productivity with increasing SSH (see also Wolf et al. 2009). SSH and SST are positively correlated, indicating that later breeding and reduced production would be expected under future ocean warming.

Changes in Variance

In addition to average state, variance is an important indicator of the impacts of change because increasing variance (or variability) of population parameters can lead to population declines even when average parameter values are stationary. Moreover, one of the predicted outcomes of global warming is greater variability in atmospheric and oceanographic conditions (IPCC 2007). With a relatively short 40-year time series, we found that variance in Cassin's auklet productivity increased significantly through time. Variance in murre productivity and auklet timing also tended to increase, while variance in cormorant productivity tended to decrease, but both of these changes were non-significant.

We found significant changes in the variance of auklet productivity, but not for murres or cormorants. Differences in diet and variability in diet may explain this observation. The productivity of Farallon auklets may be a significant indicator of the abundance of mesozooplankton, specifically euphausiid crustaceans ("krill;" *Euphasia pacifica* and *Thysanoessa spinifera*) that form the

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[2] Santora, J. A., S. Ralston, and W. J. Sydeman. (In Review). Interannual indices of California Current krill spatial organization: an integrated approach. Can. J. Fish. Aquat. Sci. Contact address: J. A. Santora, Farallon Institute for Advanced Ecosystem Research, P.O. Box 750756, Petaluma, CA 94975.

majority of their diet (Ainley et al. 1996; Abraham and Sydeman 2004; 2006; Sydeman et al. 2006). Change in the variance structure of the auklet time series appears to reflect fluctuations in krill populations in the region. Based on net samples, mostly from the southern CCE, Brinton and Townsend 2003 indicate a range contraction for *T. spinifera*, but no change in the abundance of *E. pacifica* from ~1950–94; however, these authors did not test for a change in variance in this data set. Using the Brinton central California net-based time series, Sydeman et al. 2006 showed an apparent reduction in both *E. pacifica* and *T. spinifera* abundance in the region in 2005, but the gaps in these data preclude any assessments of changes in variance. Jahncke et al. 2008 found fewer krill in 2005 than 2004. But without context of a long time series with which to evaluate both of these years, we are uncertain of how to interpret these results. In combining both net and acoustically-derived estimates of abundance and spatial organization, Santora et al.[2] show major changes in krill from 2002–06, which clearly demonstrate low krill availability to breeding seabirds in 2005 and 2006. This series captures both the high and low points in the auklet productivity time series, and shows corresponding extremes in krill availability. In the productive years of 2002–03, krill were found in large patches near the Farallones, whereas in the unproductive years of 2005–06, no large patches were found in the region. With fewer large krill patches, auklets would have a reduced probability of encountering a productive food environment in these years. We surmise that changes in krill populations were responsible, in large part, for the increase in variance in the auklet's productivity over time, but acknowledge lack of sufficient information to make a full evaluation. Lavaniegos and Ohman 2007 show a euphausiid time series for spring surveys from central California for 1950–2004, but do not include an analysis of change in variance. From a visual inspection of their graph, it appears that the variance in euphausiid abundance has increased.

In contrast to auklets, murres consume euphausiids, but also feed at higher trophic levels on juvenile rockfish and other forage fish much of the time (Roth et al. 2008). Cormorants do not consume zooplankton and are entirely piscivorous (Sydeman et al. 1997). Variance in productivity of murres increased, and decreased for cormorants, suggesting that murres may be tracking some of the same zooplankton fluctuations as the auklets. But, as they also feed on forage fish, their changes were not as substantial, so they fall between the variance trends of auklets and cormorants. For cormorants, variance in productivity decreased slightly, which suggests a more stable and consistent prey base through time, leading to more constant productivity. We know that juvenile rockfish populations have declined or changed distribution (fig. 4), thus we surmise that other forage fish, probably northern anchovies (*Engraulis mordax*), have sustained murre and cormorant productivity at less variable levels over the study period. The majority of murres' and rhinoceros auklets' diets consisted of anchovies in the 1990s and 2000s (Sydeman et al. 2001; Thayer and Sydeman 2007, respectively).

Troubling Trends or Meandering Variability?

Despite being some of the best time series data sets on seabirds globally, the relatively short duration of these studies make it difficult to parse out the relative effects of "climate change" (secular climate warming) versus "climate variability" (regime shifts/interdecadal variability). However, as we described above, trends in timing, abundance, and productivity for most parameters are consistent with predicted responses to climate change. Notably, the declines in auklet and murre "trophic chain" productivities suggest that climate change is responsible. Ocean warming may be acting to suppress food availability for some breeding and foraging seabirds. Anomalous ocean conditions in 2005 and 2006, with delayed and/or interrupted upwelling, resulted in reduced productivity for several seabird species (murres and auklets). Moreover, increases in variance/variability coupled with declining productivity will have negative population consequences for the specific populations, such as the Farallon and Triangle Cassin's auklets. Indeed, the Farallon auklet population has declined severely (by ~80%) over the past 30 years (Lee et al. 2008) and future population declines are likely (Wolf et al.[3]).

These relatively short data sets are also confounded by low-frequency variability, particularly the "regime shifts" of 1977–78 (McGowan et al. 2003) and 1989–90 (Hare and Mantua 2000). The decline in CalCOFI seabird abundance seemingly corresponds to the 1989–90 regime shift (Hare and Mantua 2000), and the increase in seabird abundance along Line P corresponds with a possible regime shift in 1998–99 to cooler conditions. In addition, we provided a simple cross-correlation analysis for auklet productivity and found correlations with the PDO and NPGO (Di Lorenzo et al. 2008). This supports the idea that low-frequency variability is driving some of the observed changes in seabird communities and populations. In the North Pacific Ocean, quasi-interdecadal variation, characterized by the Pacific Decadal Oscillation and related phenomena (PDO: Mantua et al. 1997; Hare and Mantua 2000; Victoria pattern: Bond et al. 2003), are clearly related to plankton abundance and

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[3] Wolf, S. G., M. A. Snyder, W. J. Sydeman, and D. A. Croll. Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet. Glob. Change Biol. (*Submitted*). Contact address: Shaye G. Wolf, Center for Biodiversity, 351 California St., Suite 600, San Francisco, CA 94014.

community dynamics (Peterson and Schwing 2003; Hooff and Peterson 2006), and it appears that some seabird parameters are following this mode of climate variability.

CONCLUSIONS

From the long-term seabird data presented, we attribute most of the changes described to long-term climate change, though there are certainly some patterns that could be attributed to climate variability, or most likely a combination of the two. There are also species-interactions (e.g., interspecific competition and predation) and human interactions (e.g., fisheries impacts) that have affected CCE food webs and the apparent seabird responses to climate change. From a "bottom-up" climate perspective, there are several physical oceanographic observations which support this attribution. First, as noted for the birds, observed physical changes in the CCE exhibit regional and/or onshore-offshore complexity. Second, McGowan et al. 1998, Mendelssohn et al. 2003, Di Lorenzo et al. 2005, and Field et al. 2006b found warming of the CCE at both inshore and offshore stations. However, Palacios et al. 2004 and Di Lorenzo et al. 2005 demonstrated inshore-offshore variation in changes in ocean stratification. For example, from 1950–93, the thermocline strengthened and deepened at inshore stations, but weakened and shoaled offshore (Palacios et al. 2004). Bakun 1990 hypothesized that global warming should lead to upwelling intensification, which could also have a cross-shelf signature. Indeed, for the southern CCE, Rykaczewski and Checkley 2008 showed that offshore curl-driven upwelling displayed an increasing trend over the past 50 years, whereas nearshore upwelling showed no trend. However, in the central-northern CCE, from approximately 35°–39°N, proxies of upwelling such as winds and SST have shown patterns of increase suggesting upwelling intensification in nearshore environments (Schwing and Mendelssohn 1997; Mendelssohn and Schwing 2002; Garcia-Reyes and Largier, in press). Notably, ocean warming and increased stratification may counteract increasing winds and upwelling; indeed, changes in the efficacy of upwelling, mixing, nutrient input, and corresponding biological productivity will depend on the relative strength of these opposing effects.

Some contrasting trends in productivity and variance of seabirds may reflect regional or cross-shelf changes in upwelling, physical oceanographic conditions and trophic ecology. For example, Brandt's cormorant showed increasing productivity and decreasing variance, at least through 2007 (Sydeman et al. 2001; this paper), and population increases to the mid 2000s nearly equivalent to those seen in the early 1970s (Ainley and Lewis 1974; Warzybok and Bradley 2007[4]). Cassin's auklets have shown episodic declines in productivity and increasing variance. Why the auklets and cormorants are showing contrasting trends is not understood, but may relate to their foraging distributions and trophic ecology. Auklets feed on mesozooplankton (krill) of the outer continental shelf region, whereas cormorants feed on forage fish of the inner shelf and bay habitats. Therefore, possibly due to cross-shelf variation in upwelling intensification, the food web of the outer shelf may have declined, whereas that of the inner shelf may have improved. The decline in murre (and auklet) trophic chain productivity supports this hypothesis, as many of the juvenile rockfish, especially *Sebastes jordanii* which formed the basis for the murre's offspring diet in the 1970s and 1980s, once inhabited the outer shelf domain of the Gulf of the Farallones and have since declined substantially from that region (Field et al. 2007). Data from the southern CCE also support this hypothesis. Hsieh et al. 2009 demonstrated declining trends for many oceanic mid-water fish species. Obviously, there is still much to be learned to rectify patterns of change in inshore-offshore physical oceanography and zooplankton, forage fish, and seabird populations in the CCE. This is an area ripe for research, and highlights the need to integrate spatial ecology into time-series approaches towards understanding the impacts of climate change on marine biota and ecosystems of the North Pacific Ocean.

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Part III

SCIENTIFIC CONTRIBUTIONS

IMPORTANCE OF FAR-OFFSHORE SAMPLING IN EVALUATING THE ICHTHYOPLANKTON COMMUNITY IN THE NORTHERN CALIFORNIA CURRENT

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ABSTRACT

The distribution and concentration of ichthyoplankton were examined from stations extending 2–364 km offshore at 7–53 km intervals along the Newport Hydrographic (NH) and Crescent City (CC) (July 2008 only) lines in the northern California Current (NCC) during March, April, and October 2007, and March, June, and July 2008. A total of 2372 fish larvae representing 36 taxa from 22 families were collected in 72 bongo samples from 30 stations: 15 stations were "shelf" (<2000 m depth), 15 were "far-offshore" (>2000 m depth). Four dominant taxa accounted for 90% of the total larval fish concentration: *Stenobrachius leucopsarus* (47%), *Sebastes* spp. (25%), *Engraulis mordax* (12%), and *Tarletonbeania crenularis* (6%). Mean study-wide concentrations of the dominant taxa were significantly greater in the far-offshore region than in the shelf region. Weighted mean length was significantly greater only for larval *Sebastes* spp. collected at the far-offshore compared with the shelf stations, while *E. mordax* larvae were only collected at far-offshore stations in June and July 2008. Larval distributions and concentrations were also examined in relation to variable local environmental factors (i.e. temperature, salinity, dissolved oxygen, fluorescence, and east-west Ekman transport) and basin-scale indices (i.e. MEI and PDO). Historic and ongoing survey designs used to characterize the plankton community in the NCC have usually incorporated only coastal and shelf (<~100 km offshore) stations extending out to the continental slope (~2000 m depth). Increased sampling effort at far-offshore stations will be required to adequately characterize the ichthyoplankton community of the NCC in the future.

INTRODUCTION

Ichthyoplankton surveys have long been recognized as cost-effective proxies to identify spawning locations, success, environmental requirements, essential fish habitat, and recruitment potential of marine fish stocks (Hunter et al. 1993; Houde 1997; Lyczkowski-Shultz 2006), as well as providing ecosystem indicators of environmental change (Brodeur et al. 2008) and an understanding of trophic interactions between zooplankton and important piscivores (Hunter and Kimbrell 1980). However, by focusing their sampling efforts almost exclusively on near-shore and shelf waters while neglecting to sample far-offshore waters beyond the continental slope, these surveys may not adequately sample the entire, or even primary, cross-shelf range of the dominant larval taxa of interest.

During the past 40 years, most ichthyoplankton studies conducted in the northern California Current (NCC) have focused on fish eggs and larvae collected inshore of the continental slope (Richardson and Pearcy 1977; Richardson et al. 1980; Mundy 1984; Boehlert et al. 1985; Brodeur et al. 1985; Auth and Brodeur 2006; Auth et al. 2007; Auth 2008; Brodeur et al. 2008; Parnel et al. 2008). Only three NCC studies have hitherto incorporated far-offshore ichthyoplankton samples: Waldron 1972, Richardson 1973, and Doyle 1992. However, Waldron 1972 only sampled during two months (April and May) in 1967, whereas Richardson 1973 only sampled from May to October in 1969 and only differentiated sampling effort between near-shore (<37 km from shore, ~150 m in depth) and broadly-defined offshore (37–425 km from shore, ~150–3000 m in depth) stations. Doyle 1992 reported on general ichthyoplankton densities from the NCC in 1980–87, but did not conduct any testable statistical analyses of cross-shelf distributions and concentrations.

During the two decades since the completion of Doyle's 1992 work, the NCC has experienced extreme and variable climate-induced environmental fluctuations, including multiple shifts between warm and cold regimes, El Niño and La Niña events, variability in seasonal upwelling intensity, and change in biological communities (Schwing and Moore 2000; Peterson and Schwing 2003; Brodeur et al. 2006; Hooff and Peterson 2006) that may have altered the cross-shelf distribution of the ichthyoplankton community in the region. However, all studies during that time, including the on-going National Marine Fisheries Service (NMFS) Stock Assessment Improvement Plan (SAIP), U.S. Global Ocean Ecosystem Dynamics Program (GLOBEC), and Pacific Coast Ocean Observing System (PaCOOS) monitoring projects, have focused on collecting plankton samples primarily from coastal and shelf stations, largely neglecting far-offshore waters beyond the continental slope.

The present study is the first in 20 years to examine the cross-shelf variability in distribution and concentration of ichthyoplankton collected in the NCC at regular spatial intervals from near-shore out to far beyond the continental slope during multiple seasons in two consecutive years, and the first to date to do so using testable statistical techniques. Through this, I hope to (1) compare the ichthyoplankton concentrations in the heavily-sampled coastal and shelf region to those in the under-sampled far-offshore region in the NCC; (2) relate these concentration data to local (i.e. temperature, salinity, dissolved oxygen [DO], fluorescence, and eastward Ekman transport [EET]) and basin-scale (i.e. Multivariate El Niño-Southern Oscillation Index [MEI] and Pacific Decadal Oscillation [PDO]) environmental variables and indices; (3) compare and contrast these results to those of previous studies; and (4) provide a recommendation of the extent of cross-shelf sampling that is needed to adequately characterize the ichthyoplankton community of the NCC in ongoing and future sampling efforts.

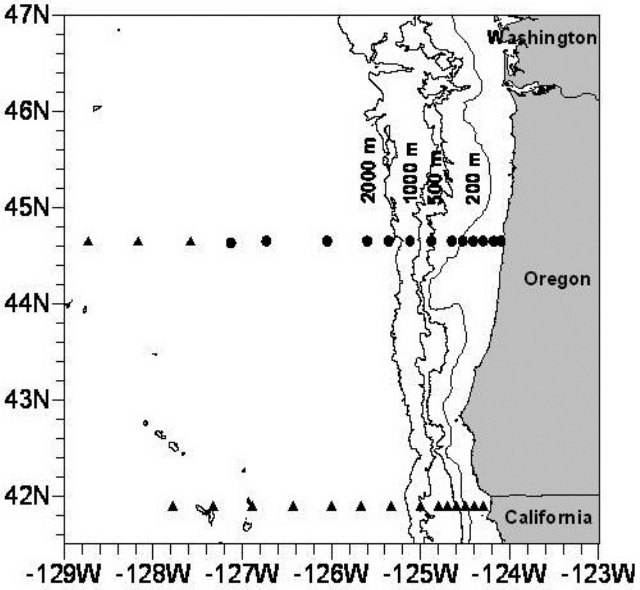

Figure 1. Locations of stations sampled in March, April, and October 2007, and March, June, and July 2008 (circles). Not all stations were sampled during each cruise. Stations indicated by triangles were only sampled during July 2008. Depth contours of 200, 500, 1000, and 2000 m (continental slope) are shown. The 2000 m isobath represents the separation between normally-sampled coastal and shelf stations and normally-unsampled slope and open ocean stations.

METHODS

Sampling procedures

A total of 72 ichthyoplankton samples were collected during the study. Samples ($n = 8$–9 per cruise) were collected from 13 stations extending 2–238 km offshore at 7–53 km intervals along the NH line (44.65°N) off the central Oregon coast in the NCC during March, April, and October 2007, and March, June, and July 2008 (fig. 1). Not all stations were sampled during all cruises. An additional 17 stations were sampled in July 2008 extending 274–364 km offshore along the NH line ($n = 3$) and 7–276 km offshore along the Crescent City (CC) line (41.9°N) ($n = 14$) off the northern California coast at 7–46 km intervals (fig. 1). Stations were sampled at different times during both day ($n = 32$) and night ($n = 40$). No significant diel differences in larval concentration were found ($p > 0.05$), therefore all samples were used in theses analyses regardless of time of sampling. Samples were collected using a bongo net with a 70 cm (60 cm in June and July 2008) diameter mouth opening and 335 µm mesh nets. The bongo was fished as a continuous oblique tow from ~45 m to the surface at a retrieval rate of 28 m/min and a ship speed of 1.0–1.5 m/s. In June and July 2008, the bongo was fished from ~100 m (or within 5 m of the bottom at stations <100 m) to the surface at the same retrieval rate and ship speed. A depth recorder and flowmeter were placed in the net during each tow to determine tow depth and volume of water filtered. The mean water-volume filtered was 132.5 m^3 (standard error [SE] = 5.7). Temperature (°C), salinity, DO (ml/L), and fluorescence (volts) (an indicator of primary productivity) were measured throughout the water column using a Seabird SBE 911 (SBE 25 in June 2008) CTD.

Because sampling was conducted as part of multiple unrelated projects, station locations, sampling depth, and mouth opening of the sampling gear were not uniform throughout the study. However, the same relative number of shelf and far-offshore stations were sampled during each cruise, and the sampling depth and gear were identical for all stations within each cruise. Since the study was designed to test for differences in larval fish concentrations between two cross-shelf regions and not between, but within, different months or years, it is not likely that the variability in sampling design over the course of the study biases the results and interpretation of any cross-shelf differences that were found.

Ichthyoplankton samples were preserved at sea in a 10% buffered-formalin seawater solution. Fish larvae from each sample were completely sorted, counted, and identified to the lowest taxonomic level possible in the laboratory using a dissecting microscope. The majority of larval *Citharichthys* spp., Osmeridae, *Sebastes* spp., and *Sebastolobus* spp. collected were not identifiable below the generic or family level based on meristics and pigmentation patterns, so no species-specific inferences are intended for these taxa in this study. However, the majority of those individuals classified as *Citharichthys*

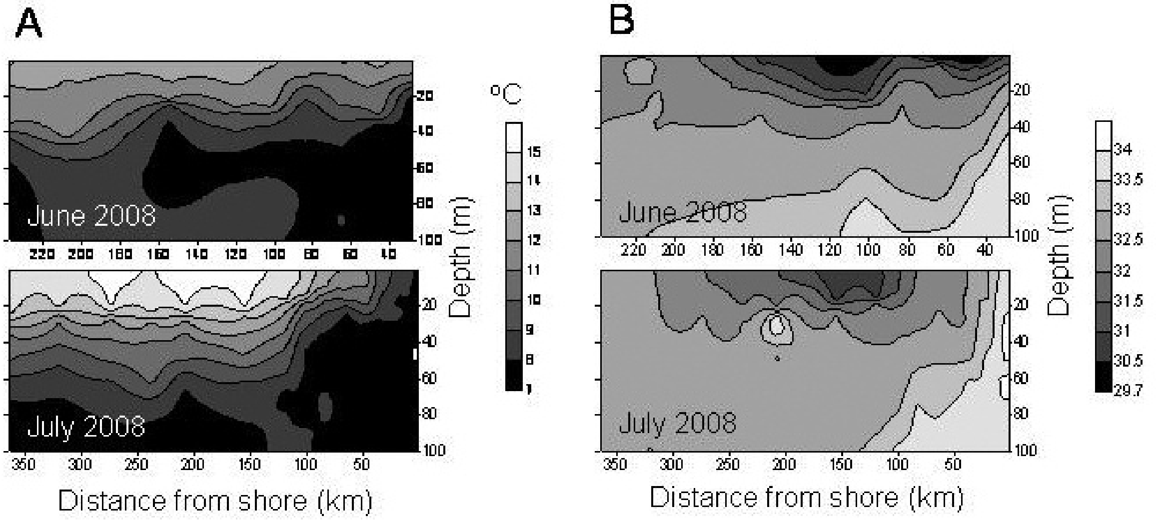

Figure 2. Cross-section of the Newport Hydrographic (NH) line showing (A) temperature (°C) and (B) salinity contours from the surface to 100 m in June and July 2008.

spp. most likely are either *C. sordidus* or *C. stigmaeus* based on the larger, identifiable individuals collected and the dominance of these paralichthyid taxa in the NCC ichthyoplankton (Matarese et al. 1989). The lesser of either all larvae or a random sub-sample of 30 individuals from each taxon in each sample was measured to the nearest 0.1 mm standard length (SL) (or notochord length for preflexon larvae) using UTHSCSA Image Tool Version 3.0 image processing and analysis software (http://ddsdx.uthscsa.edu/dig/itdesc.html 2009).

Data analyses

Along the NH line the continental slope abruptly descends from the shelf (<900 m depth) onto the abyssal plain (~3000 m depth) between 84 and 102 km offshore. To facilitate cross-shelf distributional analyses, stations were classified as either shelf (station depth <900 m) or far-offshore (station depth >2800 m) based on the location and depth of the continental slope. Larval fish concentrations were expressed as the number of individuals per 1000 m^3. An ANOVA and *t*-test were applied to the $\log_e(n + 0.1)$-transformed larval concentration data to test for significant differences between shelf and far-offshore stations. Weighted mean (based on concentration) lengths of the dominant and total larval taxa were also calculated for each station, and were similarly tested for significant differences between cross-shelf classifications.

Pair-wise correlation analyses were also conducted to assess the relationship between concentrations of several dominant taxa (*Engraulis mordax*, *Sebastes* spp., *Stenobrachius leucopsarus*, and *Tarletonbeania crenularis*) and total fish larvae, and the following environmental variables: temperature, salinity, DO, and fluorescence all measured at both 3 m and 20 m depths. The environmental variables from 3 m represent near-surface conditions, while those from 20 m represent conditions near the pycnocline and the depth stratum with the highest *Sebastes* spp., *S. leucopsarus*, and *T. crenularis* larval concentrations as reported by Auth and Brodeur 2006. Prior to inclusion in the analyses, larval concentrations were $\log_e(n + 0.1)$-transformed which normalized the data and homogenized residual variances. Statistical significance was determined at $\alpha = 0.05$. All ANOVA and correlation analyses were performed using the statistical software JMP Version 7 (SAS Institute 2007).

RESULTS

Hydrography

Temperature, salinity, DO, and fluorescence sections (not shown) showed little cross-shelf variability in March, April, and October 2007, and March 2008 (and in June and July 2008 for DO and fluorescence). Near-surface temperatures generally increased and near-surface salinities generally decreased with distance offshore. In June and July 2008, however, pronounced upwelling-induced cross-shelf variability in temperature and salinity was observed, with cold, saline water rising to the surface from depth nearshore (<50 km), while warmer, less-saline water was pushed along the surface offshore (fig. 2). The presence of Columbia River plume waters along the NH line was apparent by a patch of warm, less-saline near-surface water 100–160 km offshore in June (mean 3 m temperature = 12.3°C; mean 3 m salinity = 30.4) and 120–275 km offshore in July (mean 3 m temperature = 15.1°C; mean 3 m salinity = 31.4) 2008. Temperature at 3 m depth along the NH line varied between 9.3°–10.0°C in March, 9.8°–10.8°C in April, and 11.2°–13.6°C in October 2007, and 8.7°–9.1°C in March, 11.5°–13.0°C in June, and 7.5°–15.5°C in July 2008.

TABLE 1

Composition, frequency of occurrence, mean concentration (no./1000 m^3), and percent of total concentration for all larval fish collected off the Oregon coast at stations along the Newport Hydrographic (NH) line (44.65°N) in March, April, and October 2007, and March, June, and July 2008, as well as off the northern California coast at stations along the Crescent City (CC) line (41.9°N) in July 2008.

	Common name	Frequency occurrence	Mean concentration (no./1000 m^3)	Total concentration (%)
Clupeidae				
Sardinops sagax	Pacific sardine	0.01	0.07	0.03
Engraulidae				
Engraulis mordax	Northern anchovy	0.10	29.97	12.24
Bathylagidae				
Bathylagus pacificus	Pacific blacksmelt	0.01	0.10	0.04
Lipolagus ochotensis	Eared blacksmelt	0.08	1.48	0.60
Osmeridae				
Undetermined spp.	Smelts	0.03	1.30	0.53
Stomiidae				
Chauliodus macouni	Pacific viperfish	0.03	0.19	0.08
Tactostoma macropus	Longfin dragonfish	0.01	0.14	0.06
Paralepididae				
Lestidiops ringens	Slender barracudina	0.01	0.16	0.07
Myctophidae				
Protomyctophum crockeri	California flashlightfish	0.06	0.40	0.16
Protomyctophum thompsoni	Bigeye lanternfish	0.04	0.34	0.14
Tarletonbeania crenularis	Blue lanternfish	0.49	13.80	5.64
Nannobrachium regale	Pinpoint lampfish	0.21	2.39	0.98
Stenobrachius leucopsarus	Northern lampfish	0.68	113.91	46.53
Diaphus theta	California headlightfish	0.04	0.62	0.25
Gadidae				
Microgadus proximus	Pacific tomcod	0.01	1.73	0.71
Bythitidae				
Cataetyx rubrirostris	Rubynose brotula	0.01	0.09	0.04
Trachipteridae				
Trachipterus altivelis	King-of-the-salmon	0.01	0.09	0.04
Scorpaenidae				
Sebastes spp.	Rockfishes	0.63	61.80	25.25
Sebastolobus spp.	Thornyheads	0.13	2.04	0.83
Anoplopomatidae				
Anoplopoma fimbria	Sablefish	0.01	0.18	0.08
Cottidae				
Artedius fenestralis	Padded sculpin	0.01	0.19	0.08
Agonidae				
Bathyagonus pentacanthus	Bigeye poacher	0.01	0.06	0.03
Liparidae				
Liparis fucensis	Slipskin snailfish	0.06	0.70	0.29
Liparis mucosus	Slimy snailfish	0.01	0.34	0.14
Cryptacanthodidae				
Cryptacanthodes aleutensis	Dwarf wrymouth	0.01	0.18	0.07
Icosteidae				
Icosteus aenigmaticus	Ragfish	0.04	0.42	0.17
Ammodytidae				
Ammodytes hexapterus	Pacific sand lance	0.01	0.19	0.08
Centrolophidae				
Icichthys lockingtoni	Medusafish	0.07	0.37	0.15
Tetragonuridae				
Tetragonurus cuvieri	Smalleye squaretail	0.03	0.20	0.08
Paralichthyidae				
Citharichthys sordidus or *stigmaeus*	Pacific or speckled sanddab	0.04	0.65	0.27
Pleuronectidae				
Embassichthys bathybius	Deepsea sole	0.01	0.11	0.04
Glyptocephalus zachirus	Rex sole	0.11	2.45	1.00
Isopsetta isolepis	Butter sole	0.03	0.84	0.34
Lyopsetta exilis	Slender sole	0.18	3.04	1.24
Microstomus pacificus	Dover sole	0.08	1.21	0.49
Parophrys vetulus	English sole	0.06	2.65	1.08
Undetermined		0.01	0.14	0.06

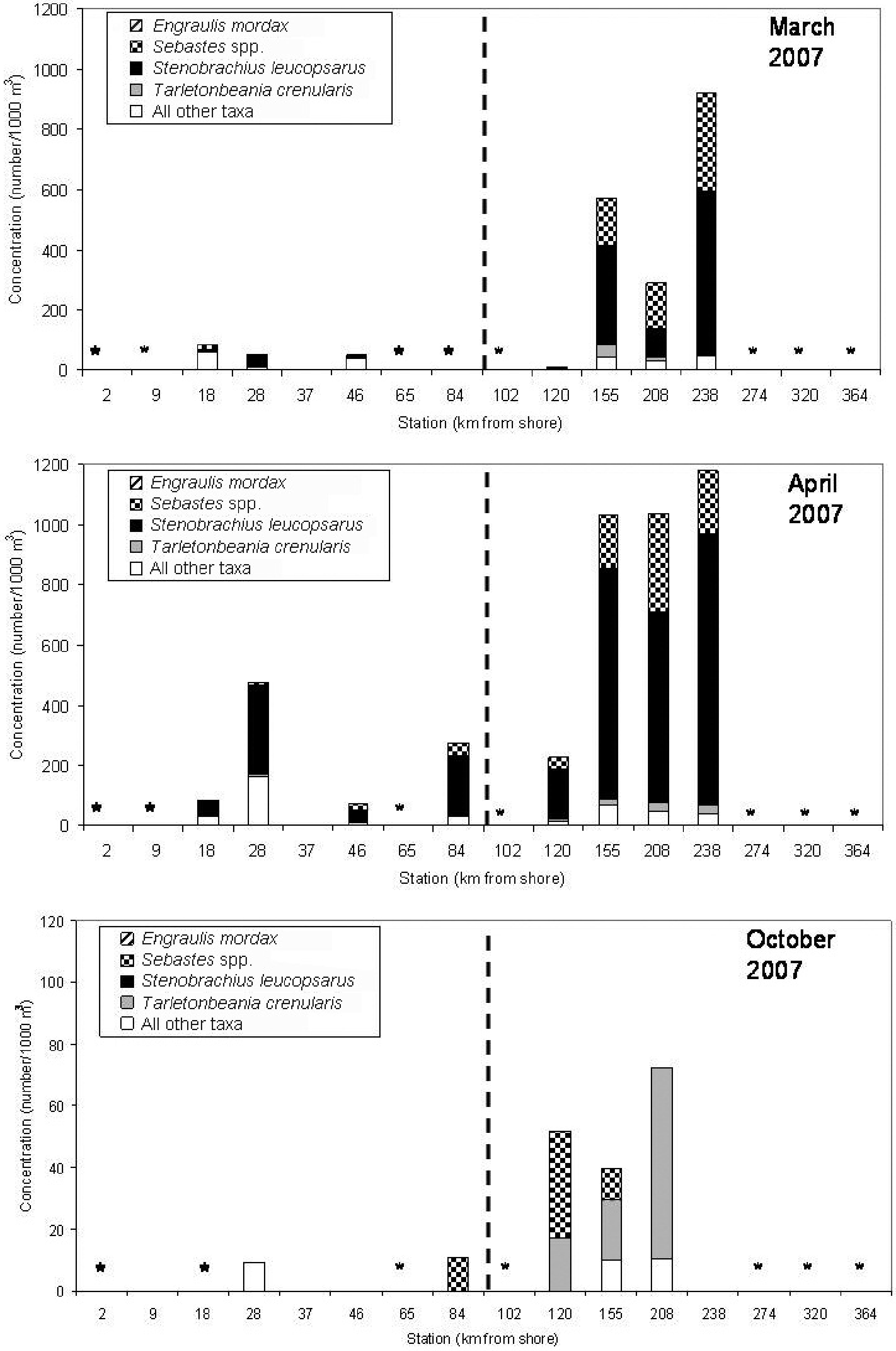

Figure 3. Cross-shelf concentrations (number/1000 m³) of the dominant larval fish taxa collected off the Oregon coast at stations along the Newport Hydrographic (NH) line (44.65°N) in March, April, and October 2007, and March, June, and July 2008, as well as off the northern California coast at stations along the Crescent City (CC) line (41.9°N) in July 2008. Vertical dotted lines indicate the separation between normally-sampled coastal and shelf stations and normally-unsampled far-offshore stations. * = station not sampled.

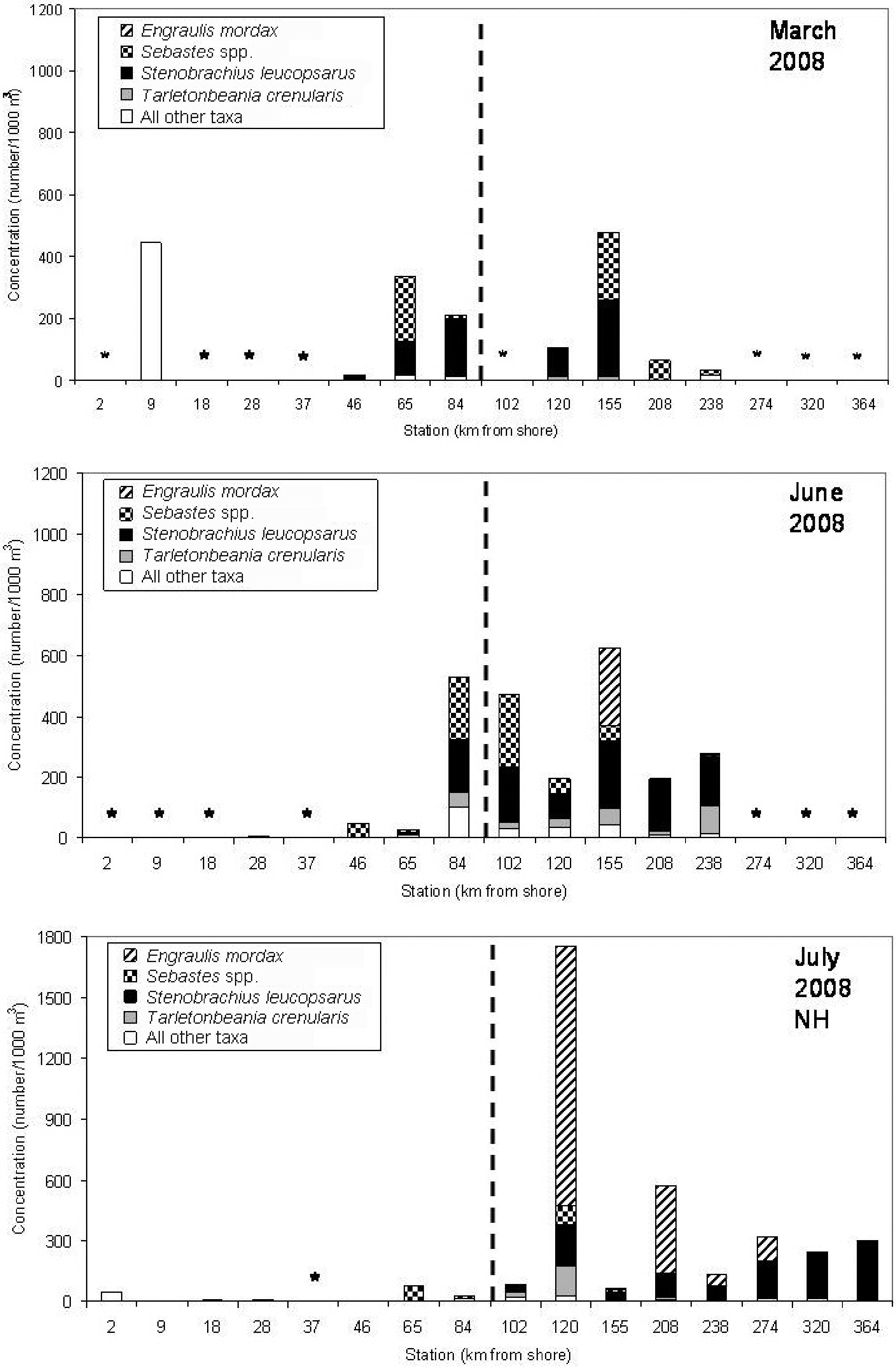

Figure 3 (continued). Cross-shelf concentrations (number/1000 m³) of the dominant larval fish taxa collected off the Oregon coast at stations along the Newport Hydrographic (NH) line (44.65°N) in March, April, and October 2007, and March, June, and July 2008, as well as off the northern California coast at stations along the Crescent City (CC) line (41.9°N) in July 2008. Vertical dotted lines indicate the separation between normally-sampled coastal and shelf stations and normally-unsampled far-offshore stations. * = station not sampled.

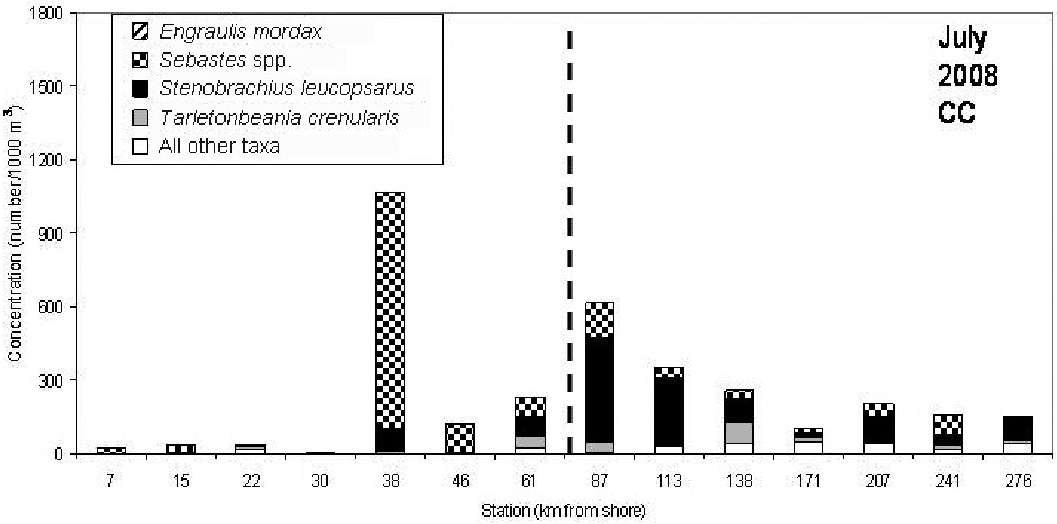

Figure 3 (continued). Cross-shelf concentrations (number/1000 m^3) of the dominant larval fish taxa collected off the Oregon coast at stations along the Newport Hydrographic (NH) line (44.65°N) in March, April, and October 2007, and March, June, and July 2008, as well as off the northern California coast at stations along the Crescent City (CC) line (41.9°N) in July 2008. Vertical dotted lines indicate the separation between normally-sampled coastal and shelf stations and normally-unsampled far-offshore stations. * = station not sampled.

Larval concentrations and distributions

A total of 2372 fish larvae representing 36 taxa from 22 families were collected throughout the study (tab. 1). Four dominant taxa accounted for 90% of the total larval concentration: *S. leucopsarus* (47%), *Sebastes* spp. (25%), *E. mordax* (12%), and *T. crenularis* (6%). Several other taxa occurred at relatively high frequencies (>0.10) but at lower mean concentrations: *Nannobrachium regale, Lyopsetta exilis*, *Sebastolobus* spp., and *Glyptocephalus zachirus*.

Mean study-wide concentrations of all dominant taxa (excluding an anomalously high *Sebastes* spp. value at the 38 km station on the CC line in July 2008) and total larvae were significantly higher in the normally-unsampled far-offshore region than the normally-sampled coastal and shelf region (fig. 3). This was particularly true for *E. mordax* larvae, which were exclusively found in the warmer Columbia River plume waters in the far-offshore region in June and July 2008. Mean study-wide concentration of *Sebastes* spp. larvae was 2.6 times higher at far-offshore than at shelf stations, with a monthly maximum of 33 times higher in March 2007. Larval *S. leucopsarus* were five times more concentrated overall at far-offshore than shelf stations, and as much as 15 times more in March 2007. *Tarletonbeania crenularis* larvae were six times more concentrated throughout the study at far-offshore than shelf stations, and were exclusively collected at far-offshore stations in half of the months sampled (March and October 2007, and March 2008). A high concentration (442.4/1000 m^3) of diverse, nearshore, non-dominant larval taxa (i.e. *Ammodytes hexapterus*, *Artedius fenestralis*, *Citharichthys* spp., *Isopsetta isolepis*, *Liparis fucensis*, *Microgadus proximus*, Osmeridae, and *Parophrys vetulus*) were also collected along the NH line in March 2008 at a station 9 km from shore, and comprised 25% of all non-dominant larvae collected throughout the study.

Study-wide weighted mean length was significantly greater for larval *Sebastes* spp. collected at far-offshore (mean = 6.1 mm, SE = 0.2) than at shelf (mean = 4.3 mm, SE = 0.2) stations ($p < 0.0001$). However, no significant cross-shelf differences in weighted mean lengths were found for either *S. leucopsarus* or *T. crenularis* larvae.

Environmental relationships

Pair-wise correlation analyses revealed that larval fish concentrations were generally positively correlated with temperature and negatively correlated with salinity (tab. 2). Concentration of larval *E. mordax* was significantly positively correlated with 3 and 20 m temperature, and negatively correlated with 3 m salinity and 3 m and 20 m fluorescence ($p < 0.05$). *S. leucopsarus* larvae were significantly positively correlated with 3 m and 20 m temperature and 20 m DO, and negatively correlated with 3 m and 20 m salinity ($p < 0.05$). *T. crenularis* larval concentration was significantly positively correlated with 3 m and 20 m temperature, and negatively correlated with 20 m salinity ($p < 0.05$). However, there were no significant correlations between any of the measured environmental variables and larval *Sebastes* spp. concentration ($p > 0.05$).

DISCUSSION

The four dominant larval taxa found in this study were among the dominant taxa reported by other cross-shelf studies conducted in the last 40 years in the NCC during spring and summer (Waldron 1972; Richardson

TABLE 2

Correlation coefficients for 13 variables sampled off the Oregon coast at stations along the Newport Hydrographic (NH) line (44.65°N) in March, April, and October 2007, and March, June, and July 2008, as well as off the northern California coast at stations along the Crescent City (CC) line (41.9°N) in July 2008: 3 m and 20 m temperature (°C) ($n = 67$), salinity ($n = 67$), dissolved oxygen (DO) (ml/L) ($n = 67$), fluorescence ($n = 54$), and $\log_e(n + 0.1)$-transformed concentrations (no. $1000\ m^3$) of *Engraulis mordax*, *Sebastes* spp., *Stenobrachius leucopsarus*, *Tarletonbeania crenularis*, and total larvae. ★ = $p < 0.05$.

	Engraulis mordax	*Sebastes* spp.	*Stenobrachius leucopsarus*	*Tarletonbeania crenularis*	Total larvae
Temperature 3 m	0.50★	−0.06	0.30★	0.40★	0.20
Salinity 3 m	−0.31★	−0.17	−0.26★	−0.19	−0.22
DO 3 m	0.11	0.01	−0.09	0.13	−0.02
Fluorescence 3 m	−0.29★	−0.04	−0.09	−0.18	−0.09
Temperature 20 m	0.47★	−0.11	0.34★	0.39★	0.20
Salinity 20 m	−0.22	−0.12	−0.33★	−0.31★	−0.28★
DO 20 m	−0.02	0.20	0.31★	0.24	0.25★
Fluorescence 20 m	−0.29★	−0.03	−0.07	−0.15	−0.14

1973; Richardson and Pearcy 1977; Richardson et al. 1980; Brodeur et al. 1985; Doyle 1992; Auth and Brodeur 2006; Auth et al. 2007; Auth 2008). A single *Sardinops sagax* larva (4.3 mm notochord length) was also collected at a station 320 km offshore along the NH line in July 2008, while several *S. sagax* eggs were collected at the furthest offshore stations (320 and 364 km offshore) along the NH line and the furthest offshore station (276 km offshore) along the CC line in July 2008. This species has only been known to spawn in the study area since the mid-1990s after an absence of nearly 40 years (Emmett et al. 2005), and would not have been detected during this study under a normal shelf-sampling-only regime.

The cross-shelf distributions of the dominant larval taxa found in this study differed in some cases from those reported by previous studies conducted in the California Current region. *Engraulis mordax* larvae were found in high concentrations and exclusively in the warm, offshore Columbia River plume waters as reported previously (Richardson 1973; Shenker 1988; Auth and Brodeur 2006). However, because the Columbia River plume was located far offshore during June and July (when peak *E. mordax* spawning occurs) 2008, these larvae would not have been detected along this transect had sampling only occurred at normally-sampled coastal and shelf stations. The myctophid larvae were much more prevalent at far-offshore than shelf stations during the present study. In the NCC region, Waldron 1972 reported more zero catches of *S. leucopsarus* and *T. crenularis* larvae in shelf than far-offshore waters, while Doyle's 1992 mean-distribution maps for 1980–87 showed marginally higher concentrations of these two taxa offshore of the continental slope. In the southern California Current (SCC) region, the 1951–98 California Cooperative Oceanic Fisheries Investigation (CalCOFI) surveys showed that *S. leucopsarus* larvae were distributed in higher concentrations inshore of the continental slope than farther offshore, while *T. crenularis* larvae were more evenly distributed (Moser et al. 2001).

Previous studies also identified variable cross-shelf distributions of *Sebastes* spp. larvae. In the NCC region, Waldron 1972 found higher concentrations of larval *Sebastes* spp. inshore of the continental slope, and Richardson 1973 reported a similar distribution between stations inshore and offshore of 37 km, while Doyle 1992 reported the highest concentrations along the continental slope. In the SCC region, the CalCOFI surveys showed that *Sebastes* spp. larvae were almost exclusively distributed inshore of the continental slope (Moser et al. 2001). Although mean concentrations of larval *Sebastes* spp. in the present study were higher in the far-offshore than the shelf region, these larvae were distributed on both sides of the slope. In fact, an anomalously high number of *Sebastes* spp. larvae ($n = 164$), around four times greater than the number found at any other station during the study, were collected at a mid-shelf station located 38 km offshore along the CC line in July 2008. However, since all of those larvae were relatively small and similar in size (mean = 4.2 mm, standard deviation [SD] = 0.6), this was determined to be an outlier resulting from small-scale spatial patchiness which can be a common confounding factor in any large-scale ichthyoplankton survey (Gray 1996).

Variations in local and basin-scale environmental factors and indices did not appear to explain the consistently higher concentrations of the dominant larval fish taxa in far-offshore than shelf and coastal waters during this study. Although *E. mordax*, *S. leucopsarus*, and *T. crenularis* larval concentrations were positively correlated with temperature and negatively correlated with salinity as previously reported (Auth and Brodeur 2006), the magnitude and direction of cross-shelf variability in these environmental factors were not consistent between the different months in which sampling occurred. In addition, MEI, PDO, and EET index values all varied between positive, neutral, and negative during the different sampling periods (fig. 4), while mean concentrations of the dominant and total larval fish taxa remained consis-

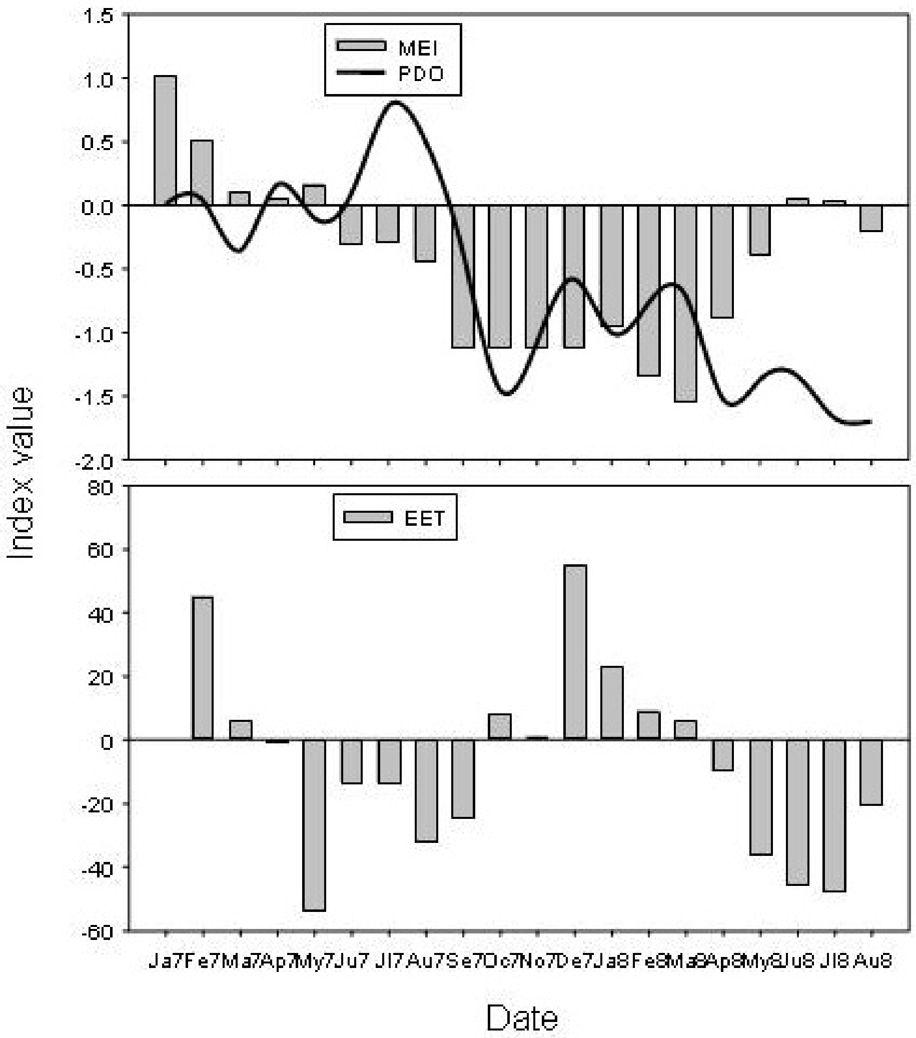

Figure 4. Monthly-averaged multivariate El Niño-southern oscillation index (MEI), Pacific decadal oscillation (PDO), and eastward Ekman transport (EET) (kg/m) from 45°N, 125°W.

tently higher at far-offshore than more-nearshore stations. Variations in seasonal or annual cross-shelf zooplankton prey concentrations and assemblages may help explain the high far-offshore larval fish concentrations observed in this study, which will be examined in a future study (W. Peterson[1]).

It is important to note that the four dominant taxa found in this study are all commercially or ecologically significant to the northeast Pacific Ocean fishery and ecosystem. Adult *Sebastes* spp. and *E. mordax* are widely harvested throughout the NCC region (Brodeur et al. 2003), while myctophids such as *S. leucopsarus* and *T. crenularis* are the dominant component of the micronekton community and represent a vital trophic link between zooplankton and piscivorous organisms in the north Pacific Ocean (Beamish et al. 1999; Brodeur and Yamamura 2005; Suntsov and Brodeur 2008, Phillips et al. 2009). With such high concentrations of the larvae of these dominant taxa being found far offshore beyond the continental slope, it would be unreasonable to assume that these individuals are lost from the system or will not recruit to the more nearshore adult community. Active or passive advection of far-offshore larvae back onto the shelf may occur as a result of larvae and juveniles regulating their position in the water column through diel vertical migrations to take advantage of selective Ekman transport and varying tidal currents (Norcross and Shaw 1984; Auth et al. 2007). If such advection does occur, then the numerous larvae found far offshore may substantially contribute to the overall recruitment of more inshore stocks, and must be considered as part of any stock assessment program incorporating an ichthyoplankton component.

Stock assessments for many of the ~40 species of *Sebastes* occurring in the NCC region are regularly con-

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[1] W. Peterson. Pers. commun. Hatfield Marine Science Center, Newport, OR 97365.

ducted as part of the fisheries management plans for the important commercial stocks within this genus. Although *Sebastes* spp. larvae could not be identified to species in this study based on meristic and pigmentation patterns, future studies may result in identification of specimens to species using molecular genetics techniques (Gray et al. 2006). This could eventually lead to the incorporation of larval abundance data in stock assessments. Variability in cross-shelf location and seasonal timing of spawning may occur for different species of *Sebastes* within the NCC region (Love et al. 2002). This may contribute to the cross-shelf and seasonal variability in concentration and length of *Sebastes* spp. larvae found in this study. The more numerous, larger larvae found far offshore may be different species than the less numerous, smaller larvae collected over the shelf, or could represent an advection of recently-spawned larvae of similar species composition from more-nearshore to farther-offshore waters through ontogeny. If the species composition and spawning time is similar in the two cross-shelf regions, then the larger size of the far-offshore larvae could be due to an increased growth rate resulting from increased prey quantity and/or quality in the far-offshore region. In any case, with a pelagic larval-stage duration of one to two months and a juvenile stage lasting weeks to months before demersal settlement (Love et al. 2002; Matarese et al. 2003), early-life stages of *Sebastes* spp. could accomplish cross-shelf migrations in search of optimal environmental conditions and prey availability before finally settling in coastal and shelf waters.

Evidence for *Sebastes* spp. surviving into the juvenile stage in far-offshore waters was found in June 2008, when the highest concentration (4.4/1000 m^3) of *Sebastes* spp. juveniles (mean SL = 23.9 mm, SD = 2.4) ever recorded out of all 176 mid-water trawl samples containing at least one *Sebastes* spp. individual from the 2004–08 SAIP survey was collected at a station 208 km offshore along the NH line[2]. This was the only mid-water trawl conducted at such a far-offshore station in the five years of the SAIP survey, and represents a concentration almost three times higher than that found for *Sebastes* spp. juveniles at any other station to date. Not only does this suggest that early-life stages of *Sebastes* spp. can survive in far-offshore waters through ontogeny, but also brings into question the effectiveness of marine protected areas for this genus designated solely in coastal and shelf waters if adults are spawning in farther-offshore waters.

The results from the present study showed that not only are the dominant fish larvae in the NCC region, comprising commercially and ecologically important taxa found in normally-unsampled far-offshore waters beyond the continental slope, but that they exist in higher concentrations in this area than in the normally-sampled coastal and shelf waters. Ongoing and future sampling designs should incorporate far-offshore stations at least 100 km beyond the continental slope if they are to truly capture the entire community structure of ichthyoplankton in the NCC. This could be accomplished with little or no additional resources of ship and personnel time by reducing the fine-scale latitudinal spacing of stations in favor of a broader and more complete cross-shelf coverage as previously suggested by Auth 2008.

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COMPARISONS OF LIDAR, ACOUSTIC AND TRAWL DATA ON TWO SCALES IN THE NORTHEAST PACIFIC OCEAN

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ABSTRACT

We compared measurements of integrated optical volume backscattering coefficients $\beta(\pi)$ with integrated acoustic volume backscattering coefficients (s_v) and surface-trawl catches over a large-scale (roughly 300 km by 450 km) region, and a small-scale (roughly 50 km by 50 km) region off the coasts of Oregon and Washington. In both cases, the data were significantly correlated. For the large-scale data, the correlation was better ($R = 0.78$) when the lidar data were collected at night compared to during the day, probably because the fish ascend into the near-surface layer at night. For the small-scale survey, lidar data were only collected at night, and the correlation was higher ($R = 0.98$). With the large-scale data set, we performed a simulation of an adaptive sampling technique that would use the airborne lidar to direct the acoustic survey. This could significantly reduce ship time with only a modest decrease in the quality of the results.

INTRODUCTION

Pacific sardine (*Sardinops sagax*) is currently one of the dominant pelagic fish species in the northern California Current and is an important ecological component of this ecosystem (Emmett et al. 2005). Since sardines are commercially important, accurate stock assessments are important for successful management. They are presently assessed by a combination of acoustic/trawl surveys and egg production estimates (Emmett et al. 2005; Hill et al. 2006; Cutter and Demer 2008). Their abundance fluctuates greatly over a vast region of the California Current, so comprehensive ship surveys are expensive.

However, sardines often form near-surface schools that have patchy distributions over large areas, and this behavior suggests that aerial survey data could aid assessments and thus those responsible for management.

Detection of fish schools by airborne lidar was demonstrated originally by Squire and Krumbolts (1981). More recently, comparisons of lidar and echosounder measurements of capelin and herring (Brown et al. 2002), mullet and baitfish (Churnside et al. 2003), zooplankton (Churnside and Thorne 2005), and epipelagic juvenile fish (Carrera et al. 2006) have demonstrated good agreement when the measurements were made within a few days and both lidar and echosounder data were appropriately filtered to remove unwanted signals.

In this study, the results of aerial lidar surveys were compared with those from a large-scale echosounder survey off the coast of Oregon and Washington and a small-scale trawl survey near the mouth of the Columbia River. Various algorithms were applied to the lidar data, and their correspondence with the echosounder and trawl results investigated. The results were similar to those of previous studies (Carrera et al. 2006; Churnside et al. 2009a), which found median filtering and thresholding of lidar data to produce good correlation with ship survey results. The data from the large-scale survey were also used to retrospectively investigate how the lidar survey might have been used to direct an adaptive survey with the ship.

METHODS

The study area for the large-scale survey (fig. 1) extended from near the shore out to almost 128°W and from 44° to 48°N. The FV *Frosti* collected acoustic data along constant-latitude lines during the day, and oceanographic profiles and surface trawls at night. The National Oceanic and Atmospheric Administration (NOAA) Fish Lidar was flown out and back along the same transect line during the afternoon of the acoustic survey and again starting at least one hour after sunset that same evening. The five transect lines were flown on July 9 (44°N), 10 (45°N), 11 (46°N), 13 (47°N), and 16 (48°N) in 2003.

The echosounder (Simrad ES60) was configured with a 38 kHz split-beam transducer (Simrad ES38-B; 7° beam width), hull-mounted at a nominal depth of four meters. Volume backscattering strengths (S_v) less than -55 dB (re 1 m^{-1}) or greater than -25 dB were removed. The remaining volume backscattering coefficients (s_v) (per m) were integrated from depth $d = 7$ m (three meters below the transducer) to $d = 254$ m, and averaged over 0.5°-longitude intervals along each transect, resulting in 39 area-backscattering coefficients (s_a)(m^2/nmi^2).

The NOAA Fish Lidar (Churnside et al. 2001; Churnside 2008) transmitted a short (12 ns), intense (120 mJ)

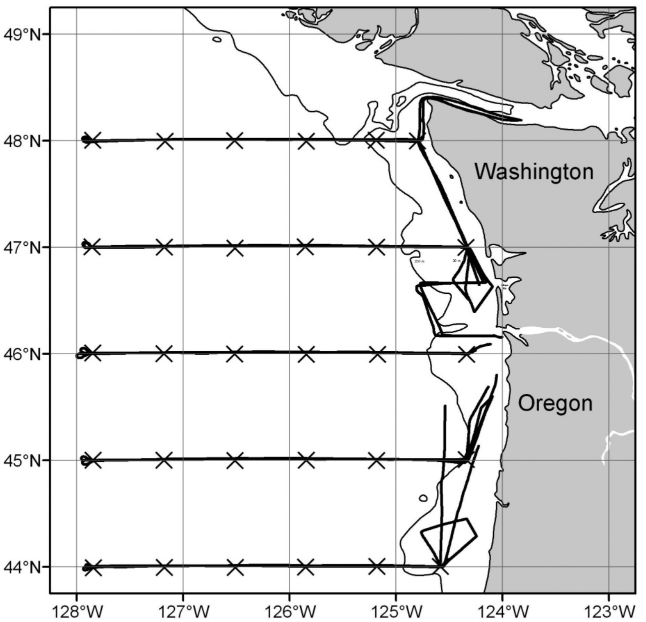

Figure 1. Chart of large-area survey region showing all flight tracks (heavy black lines) and oceanographic sampling stations (X) off the coast of Oregon and Washington in July 2003. The light black line is the 200 m isobath. Acoustic data were collected along the lines defined by the flight tracks and oceanographic stations.

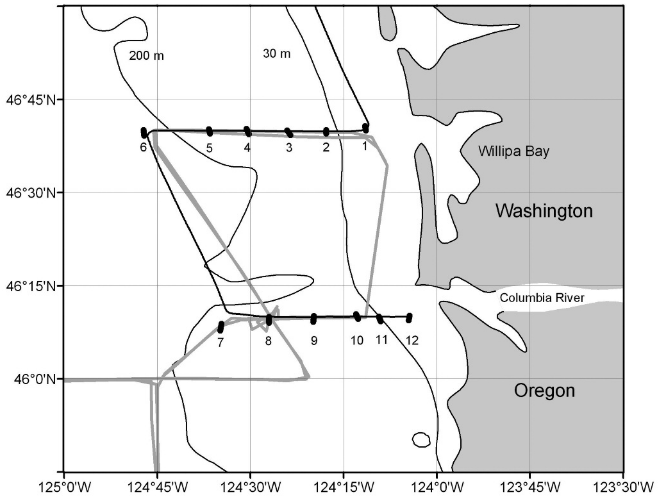

Figure 2. Chart of small-area survey region showing trawl lines of 12 trawl stations and flight tracks for the nights of 16 July (black) and 17 July (grey) 2003.

pulse of green (532 nm) laser light that was diverged to produce a 5 m diameter spot on the sea surface. The receiver used a 17 cm diameter telescope to collect the backscattered light onto a photomultiplier tube. A polarizing filter rejected light in the same plane as the laser beam, while allowing light depolarized by scatterers in the air and the ocean to pass through. The detector output was log-amplified and digitized at 10^9 samples per second, which corresponds to one volume backscattering coefficient ($\beta(\pi)$) measurement every 11 cm through the upper water column. The aircraft flew at an altitude of 300 m and at a speed of 90 m/s. At this speed, and with a pulse-repetition frequency of 30 Hz, the laser pulses were separated horizontally by 3 m.

The first lidar data-processing filter, denoted "linear," was based on the assumption that background scattering within the water column was constant with depth for each pulse. This implies that the logarithm of the background-$\beta(\pi)$ profile is linear. The function:

$$\beta(\pi) = a(\exp(2\alpha d)) + b,$$

where a is a proportionality constant, α is the attenuation coefficient, and b is a constant offset, was estimated from the $\beta(\pi)$ between a depth of 2 m and at the depth of the lower limit, where the signal initially drops below 10 standard deviations of the electronic noise of the receiver. Measurements of $\beta(\pi)$ from the top 2 m were occasionally contaminated by breaking waves and bubbles; those from depths below the lower limit were affected by noise. The fitted function was used to estimate $\beta(\pi)$ and α for each pulse. Where $\beta(\pi)$ was greater than the background-$\beta(\pi)$ by a factor greater than a threshold T, it was assumed to be from fish, and it was included in the integration. The integration in this case was done over all depths between the endpoints of the fit and averaged over 0.5°-longitude segments of the flight track (bins) to match the s_a bins. Two values of integrated $\beta(\pi)$ were produced for each bin from measurements from each flight; one going west and the other east over the same trackline. These two values were averaged.

The second lidar data-processing filter, denoted "median," was based on the assumption that the background $\beta(\pi)$ at any depth was uniform along some segment of the flight track. The background $\beta(\pi)$ and α for each segment along the flight track were estimated from the median profile of the pulses within that segment, so the segment length represents the length of the median filter. The application of a threshold and the integration were done as in the linear filter.

The study area for the small-scale survey (fig. 2) was defined by the Northwest Fisheries Science Center's Predator Survey, which is a surface trawl survey of pelagic fish (Emmett et al. 2005). This survey consists of 12 trawls along two east-west transects, one off the mouth of the Columbia River and the other to the north. The trawls were made on the nights of 16 (Stations 1–6) and 17 (Stations 7–12) July 2003. Two flights were made on the same nights along the tracks shown in the Figure 2 at a speed of about 80 m/s.

Fish were sampled at night using a Nordic 264 rope trawl (NET Systems[1], Bainbridge Island, Washington)

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

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. 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 squid, a 6.1 m long, 0.8 cm mesh knotless liner was sewn into the codend.

Fish captured in trawls were separated by species, counted, and fork length (FL) (mm) was measured for up to 50 of each species. However, for very large catches, a subsample was measured, counted, and weighed; the remaining fish of each species were weighed collectively. The total number of each species was then estimated using the known number of fish per kg. Density was calculated by multiplying the number of each species in a haul by the volume of water the net fished, and standardized to number per 10^6 m^3. The volume of water fished was calculated from the trawled distance multiplied by the effective net-mouth area (336 m^2).

For comparison with net catches, the lidar data were processed in the same way as for the large-scale survey, except for the size of the bins used for averaging. The 0.5°-longitude bins used for the large-scale survey were far too large for the small-scale survey, so a bin was defined for each trawl station instead. For Stations 2–5 and 8–11, the bin extended from the midpoint of the trawl to the stations before and after the trawl. The bins at the ends on the two lines included measurements of $\beta(\pi)$ from within a circle with a radius equal to half the distance to the nearest bin.

For each combination of lidar data and acoustic or catch data, the Pearson sample correlation coefficient R was calculated. The significance p of each correlation was estimated using Student's t test.

RESULTS

For the large-scale survey, the correlation coefficient R for each combination of parameters is presented in Table 1. The acoustic data were compared separately with the daytime survey and with the night-time survey. The statistical significance of R increases with increasing R, so that any value of $R > 0.4$ has a significance $p < 0.01$. For the daytime lidar data, the correlation is only significant ($p < 0.01$) using a median filter with a threshold of one. The correlation for these cases decreases with increasing filter length. For the night-time lidar data, the situation is somewhat different. The correlation using a median filter with a threshold of one is nearly 0.73, with no dependence on the length of the filter. This correlation is significantly greater than during the daytime.

TABLE 1
Correlation coefficient (*R*) between echosounder and lidar data for the large-scale survey, with daytime and night-time lidar data considered separately.

Filter	Length (m)	Threshold	*R* (daytime)	*R* (night-time)
linear	—	1	0.38	0.65
linear	—	2	0.03	0.56
linear	—	3	−0.04	0.15
median	75	1	0.52	0.73
median	75	2	0.20	0.32
median	75	3	0.21	0.12
median	150	1	0.49	0.72
median	150	2	0.27	0.36
median	150	3	0.27	0.22
median	300	1	0.47	0.74
median	300	2	0.30	0.48
median	300	3	0.29	0.33
median	750	1	0.45	0.73
median	750	2	0.32	0.77
median	750	3	0.29	0.69
median	1500	1	0.44	0.74
median	1500	2	0.33	0.78
median	1500	3	0.32	0.52

TABLE 2
Density (number of fish per 10^6 m^3) for each haul by species, and total catch of all species from the Predator Survey in July 2003.

Haul Number	Eulachon	Northern Anchovy	Pacific Herring	Pacific Sardine	Total
1	73.22	79.68	4.31	0	157.20
2	0	1502.59	3143.19	64293.50	68939.27
3	0	43.04	557.71	147.85	748.60
4	0	10.79	113.33	0	124.12
5	0	0	105.15	2.19	107.34
6	0	0	0	0	0
7	0	2.82	227.20	0	230.02
8	0	227.72	13.49	462.18	703.40
9	0	60.20	6.69	6739.34	6806.23
10	44.92	8.17	57.17	22.46	132.71
11	23.69	17.77	1.97	0	43.44
12	0	12.07	60.36	0	72.44

The catch results for the small-scale survey are presented in Table 2. It is important to note that 88% of the total density was recorded at Station 2. Also, 92% of the catch was sardine.

The density of total fish was compared with the measured $\beta(\pi)$ to investigate the effects of filter type, filter length for the median filter, and threshold level. The significant ($p < 0.01$) correlations are presented in Figure 3. The results in the Columbia River plume show very high correlations for the smaller filter lengths and the highest thresholds that produced meaningful results.

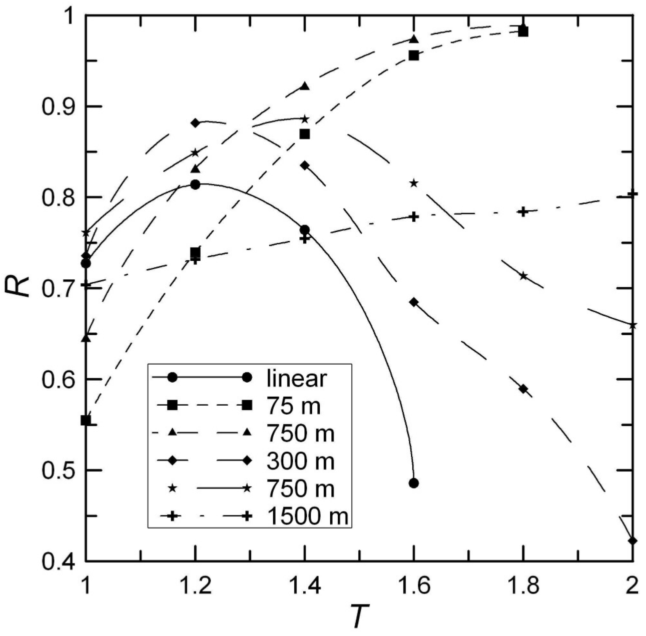

Figure 3. Correlation coefficient R between density of all fish in the surface trawls and the light backscatter as a function of threshold level T for the linear filter and the median filter with varying filter length for 2003 small-scale survey.

Increasing the threshold beyond $T = 1.8$ removed all of the $\beta(\pi)$ from most of the lidar averaging bins. Most of this correlation is due to the one very large value in both the density and the lidar backscatter. However, this is not the only correspondence. For example, there is a high correlation ($R = 0.996$, $p = 10^{-8}$) between the density of northern anchovy in the catches and the lidar signal with a filter length of 75 m and a threshold value of 1.8. Anchovy made up a small fraction of the total catch (2.5%), but were strongly associated with sardines ($R = 0.995$, $p = 10^{-6}$).

DISCUSSION

There are several interesting patterns of correlation in the large-scale survey results. These are very different in the daytime and night-time lidar data. The lidar data suggest that more of the fish that are in the depth range of the echosounder during the day ascend closer to the surface at night. These patterns are consistent with observations of sardine migrating closer to the surface and forming larger, less dense aggregations at night (Krutzikowsky and Emmett 2005; Cutter and Demer 2008). Previous computer simulations with another pelagic species that migrates vertically (northern anchovy, *Engraulis mordax*) confirm that night-time surveys will be less biased due to the fraction of the population which resides below the lidar-observation depth during the day (Lo et al. 2000).

Since higher thresholds remove contributions from weaker scatterers, it is clear that the acoustic targets are not strong lidar scatterers. Also, the median filter will remove contributions from objects larger than half of the filter length. The schools observed with the echosounder are generally smaller than about 40 m during the daytime. When the filter length is greater than 80 m, the lidar can detect objects larger than 40 m that would not be seen by the echosounder. These large objects could be plankton layers, which were visually detected in the lidar data (Churnside and Donaghay 2009). That there is no dependence on filter length suggests that the contribution from larger objects like plankton layers is negligible. For lower filter lengths (≤300 m), the correlation decreases as the threshold increases. This implies that a significant fraction of the $\beta(\pi)$ from fish is less than the threshold value. For the greater filter lengths, the correlation at $T = 2$ is slightly greater than that at $T = 1$. The implication is that there is a greater range of school size at night.

An adaptive survey was simulated using the night-time lidar data with a median filter of length 1500 m. The ship went more than 200 nm offshore on all of the transects, but most of the fish were much closer. If it were known a priori that there were no fish at the west end of the transects, the ship could have covered a smaller area with insignificant degradation of the results. For example, assuming that the ship would be sent to all regions where the $\beta(\pi)$ was above 1% of its maximum value, and using a $T = 1$, the ship would only need to survey 64% of the original area, but would still sample 89% of the acoustic backscatter from the full survey. This suggests that ship costs can be significantly reduced with little reduction in the quality of the survey. Increasing the threshold to $T = 2$ eliminates less dense aggregations of fish. In this case, with a focus on the denser schools, the ship time is reduced to 28% of the original, but the simulated survey still samples 70% of the acoustic backscatter. Specific cost/benefit analyses need to be performed for future surveys, but the unmistakable conclusion is that survey costs could be reduced using adaptive survey techniques based on the combination of data from airborne lidar and ship-based echosounders.

Remote sensing of pelagic nekton, combining aerial imagery and lidar with ship-based echosounder and direct sampling can provide a more accurate assessment at a lower cost than direct sampling alone (Churnside et al. 2009b). Lidars and echosounders provide complementary information but sample different parts of the water column. Lidar samples to the surface, but can only observe 10–50 m into the water column, depending on water clarity. An echosounder can sample to greater depths than a lidar, and either measures the fraction of the population below the lidar observation depth, or ensures that the lidar is sampling the entire population, depending on conditions.

Lidar can overcome some of the limitations that acoustical techniques have in detecting very shallow fish.

Lidar can detect fish at the surface, above the depth of a hull-mounted transducer and its associated near-field dead zone (Holliday and Larsen 1979). In addition, fish do not avoid aircraft, as they sometimes do for surface vessels (Fréon and Misund 1999). Moreover, lidar surveys can sample large areas quickly, providing synoptic views, but cannot stop to sample fish aggregations to get more detailed information. An echosounder can be used to direct scientific fishing, but may not be able to cover a large area fast enough to prevent aliasing of temporal scales into spatial scales. Thus, when possible, a combination of the two remote-sensing techniques, with complementary trawling to provide identification of the targets, could be used to provide rapid and reliable assessments of epipelagic species (Gauldie et al. 1996; Santos 2000; Churnside et al. 2009b).

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OCCURRENCE OF PLASTIC MICRO-DEBRIS IN THE SOUTHERN CALIFORNIA CURRENT SYSTEM

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ABSTRACT

We analyzed the spatial distribution, concentration, and characteristics of plastic micro-debris in neuston samples from the CalCOFI region off the southern Californian coast from winter cruises in 1984, 1994, and 2007. By sorting archived CalCOFI zooplankton samples we were able to separate micro-debris particles and characterize particle size, circularity, and surface area using digital image analysis by ZooScan. Our results suggest that plastic micro-debris is widespread in the California Current system off the southern California coast. Fifty-six to 68% of the CalCOFI stations had detectable plastic micro-debris. The average concentrations and masses of the particles were not significantly different over the three decades. Median concentrations of plastic micro-debris ranged from 0.011–0.033 particles/m^3 in different years, with a maximum of 3.141 particles/m^3. Our results also suggest that not only is plastic micro-debris widely distributed, it has been present in the northeast Pacific Ocean water column for at least 25 years.

INTRODUCTION

Marine debris is becoming a global issue, affecting diverse ocean regions, both in the neuston and below the water's surface (Sheavly and Register 2007; Arthur et al. 2009). The geographic distribution of marine debris, and its effects on ocean ecosystems, have only recently begun to be investigated (Moore 2008). Marine debris originates from either terrestrial sources (e.g., beach and other coastal accumulations, or through rivers) or from oceanic sources (e.g., ships or from offshore installations; Williams et al. 2005). Regardless of origin, marine debris could have impacts on marine organisms, habitats, and human economies (e.g., Smith et al. 1997; Derraik 2002; Lattin et al. 2004; McDermid and McMullen 2004; Sheavly and Register 2007; Moore 2008; Hinojosa and Thiel 2009; Santos et al. 2009).

Gregory and Ryan (1997) reported that plastics comprise 60%–80% of marine debris. These plastics are a rapidly growing segment of the U.S. municipal solid waste (MSW) stream. Plastics constituted less than 1% of MSW generation in 1960, increasing to 12% in 2007 (EPA 2008). Marine plastic debris has been divided into two size classes for ease of description: macro (>5 mm) and micro debris (<5mm; Arthur et al. 2009). Plastic micro-debris is composed of fragments of manufactured plastic products and pre-production plastic pellets from which plastic objects are manufactured (McDermid and McMullen 2004). Little is known about the occurrence, abundance, and effect of these plastic micro-particles in the pelagic zone of the ocean. In addition, there is little quantitative information on changes of plastic particles in the ocean over time (cf. Thompson et al. 2004). Without such information, it is difficult to assess whether plastic micro-debris is a recent addition to the ocean or has existed for an extended period of time.

Here we sought to determine whether there has been a change in the presence of plastic micro-particles in the California Current system over a multi-decadal time scale. To address this question we analyzed winter CalCOFI (California Cooperative Oceanic Fisheries Investigations) manta tow samples over three decades, from selected winter cruises in 1984, 1994, and 2007, the latter originating from Doyle et al.[1]

METHODS

Zooplankton samples for this study were collected on three CalCOFI cruises (RV *David Starr Jordan* cruise 8401 during 4–16 January 1984, RV *David Starr Jordan* cruise 9401 during 20 January–5 February 1994, and RV *David Starr Jordan* cruise 0701 during 12–29 January 2007) using the manta net neuston sampler (Brown and Cheng 1981) towed off the side of the research vessel in water undisturbed by the ship's wake. These years were selected to represent one year from the 1980s, 1990s, and 2000s, avoiding El Niño years; time and resources did not permit additional analyses. Samples were archived in the Pelagic Invertebrates Collection of the Scripps Institution of Oceanography. Only samples from the southern sec-

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[1] Doyle, M. J., W. Watson, N. M. Bowlin, and S. B. Sheavly. In Review. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific Ocean. Contact M. Doyle at: Miriam.Doyle@noaa.gov

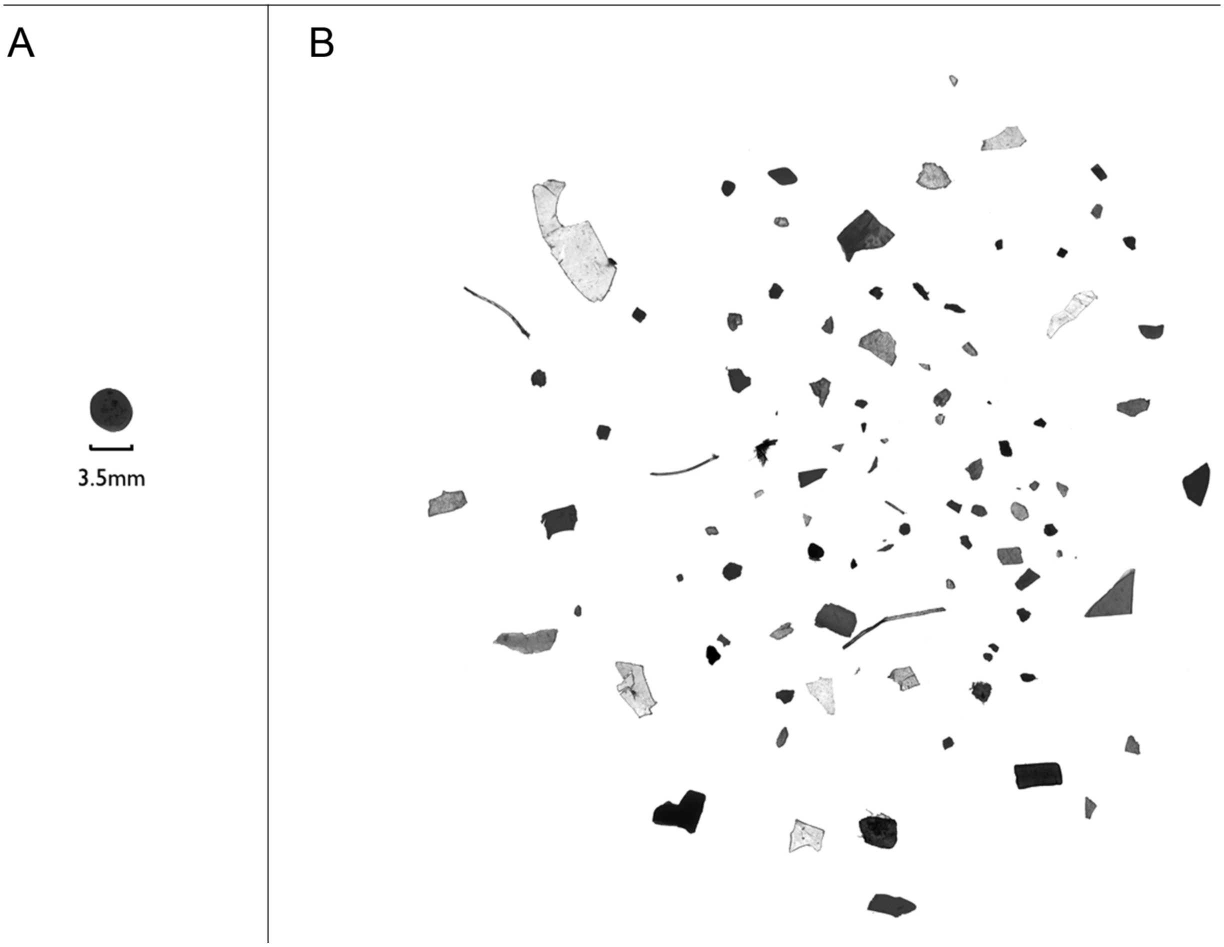

Figure 1. ZooScan images of plastic micro-debris particles from two CalCOFI stations off southern California on cruise 9401: (A) Line 83.3, station 40.6, and (B) Line 86.7, station 60. Scale bar (3.5 mm) applies to both panels.

tor of the California Current system, in the region currently occupied by CalCOFI, were considered. Specific tow times and dates for each station may be obtained from: http://collections.ucsd.edu/pi/index.cfm. Winter cruises were selected because previous analyses suggested that plastic debris is relatively widespread in the CalCOFI region at that time of year (Doyle et al.[1]). Most of the samples from 2007 had already been analyzed by Doyle et al.[1], but we were able to increase the number of samples analyzed from that cruise to 66 samples. Tow duration for the manta net was approximately fifteen minutes at a speed of 0.5–0.75 m/s, with a net mesh of 0.505 mm. After retrieval of the neuston sample, all collected material was carefully washed into the cod end and preserved in a glass sample jar in a 1.8% solution of sodium tetraborate-buffered formaldehyde in seawater. A calibrated flowmeter was fitted in the mouth of each net and the flowmeter readings were converted to cubic meters of water filtered.

We utilized the sample sorting protocol described by Doyle et al.[1] Briefly, each sample was sorted at 6X magnification using a Wild M-5 binocular dissecting scope. All inorganic marine debris (plastic, metal, glass, paint, etc.) was removed from each sample and placed in a labeled vial. The debris items were then sorted a second time to separate the plastic particles from remaining debris. All our analyses herein refer exclusively to plastic debris particles. These plastic particles were rinsed with de-ionized water and oven dried at 55°C for 8–12 hours. Dry mass was determined to the nearest 0.00001 gm using an analytical balance. The dry mass of plastic micro-debris particles for each sample was standardized according to the volume of water filtered by the sampling gear, and recorded as dry mass in mg/m^3 of seawater.

After recording dry mass, plastic micro-debris particles from cruises 8401 and 9401 were digitally imaged with a ZooScan digital scanner (Grosjean et al. 2004; Gorsky et al., in press). Particles from 0701 were not available for these analyses. Linear dimensions, surface area, and circularity of individual particles were measured using ImageJ-based tools in Zooprocess software, calibrated against manual measurements (Gorsky et al., in press). Feret diameter is the longest distance between any two points along the boundary of an object, and is

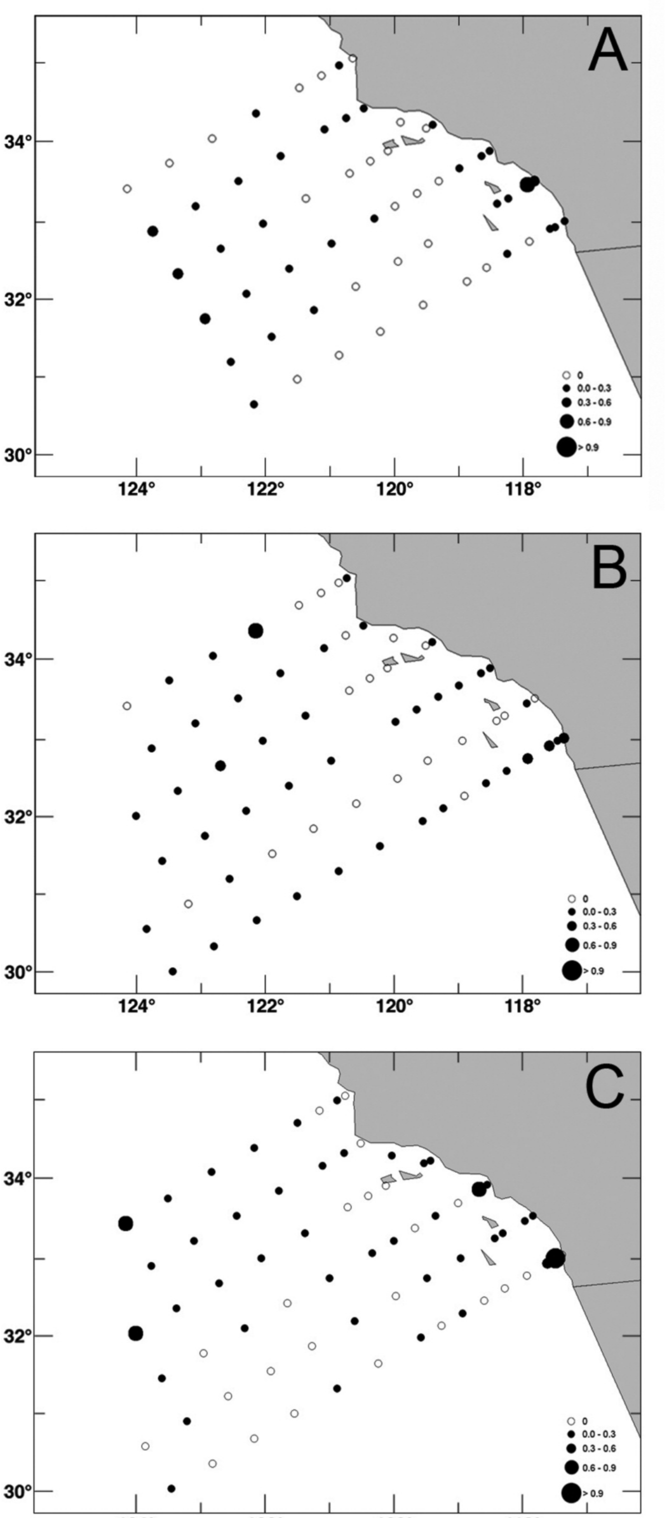

Figure 2. Spatial distribution of plastic micro-debris particles in the winter CalCOFI Manta net samples from cruises (A) 8401, (B) 9401, and (C) 0701. Open circles indicate no plastic debris detected and filled circle diameters are proportional to particle concentrations (No./m³).

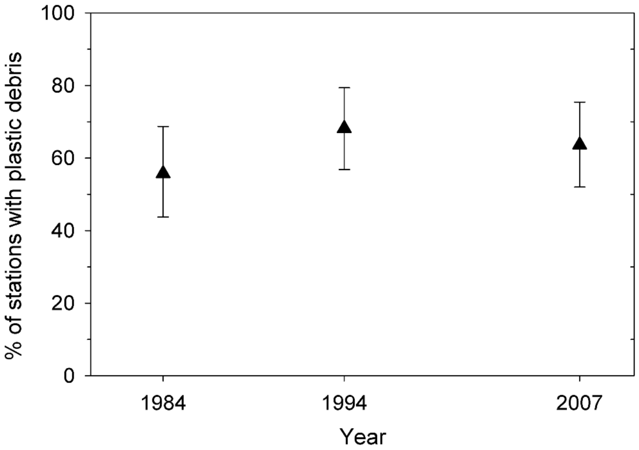

Figure 3. Temporal variation in percentage of stations from winter CalCOFI cruises with plastic micro-debris (mean ± 95% C.L. based on binomial distribution).

closely related to total length (Gorsky et al., in press). Circularity is defined as 4π (area)/perimeter², which ranges from 0 to 1, with 1.0 indicating a perfectly circular object. Figure 1 illustrates examples of ZooScan images of plastic micro-debris from two of our samples. The circularity of the pre-production plastic pellet in Figure 1A is 0.711, while circularity of the elongate rectangular piece of plastic bearing a notch, toward the upper left of Figure 1B is 0.124.

RESULTS

Plastic micro-debris was found in neuston samples at the majority of stations sampled on all CalCOFI cruises (fig. 2). Debris was detected in the inshore, transitional, and offshore regions of the sampling pattern. There was no relationship between the numerical concentration of particles and distance of collection locations from shore, or between the mass concentration of particles and distance from shore, for each cruise considered separately ($p > 0.20$) or for all cruises combined ($p > 0.20$, Spearman rank correlation). The original data are tabulated in Appendix 1.

The number of stations with plastic micro-debris particles was 34 out of 61 stations (55.7%) in 1984, 45 out of 66 stations (68.2%) in 1994, and 42 out of 66 stations (63.6%) in 2007 (fig. 3). None of the years differed in percentage of stations with plastic debris ($p > 0.05$, based on binomial confidence limits).

Concentrations of plastic micro-debris particles were highly variable across the sampling region (figs. 2, 4). The highest particle concentration (3.141 debris particles/m³) was found in 2007 at the southeastern-most point of the CalCOFI station grid near San Diego (fig. 2C). Relatively high concentrations of particles were found near San Diego, or just north of San Diego, on each cruise. Frequency distributions of particle concentrations were

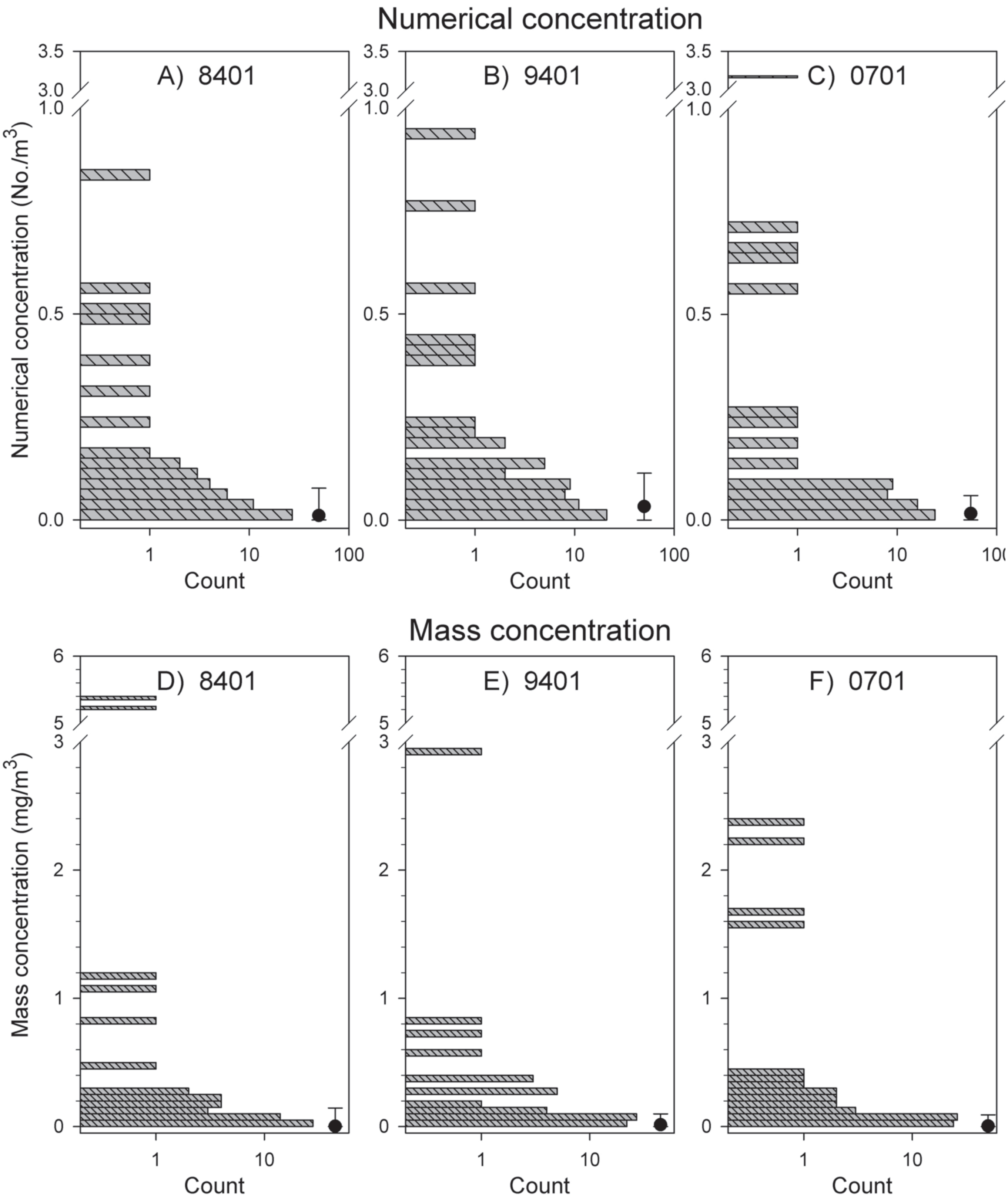

Figure 4. Frequency distributions of numerical concentrations of plastic particles (No./m^3, panels A, B, C) and dry mass concentrations of plastic particles (mg/m^3, panels D, E, F) over CalCOFI cruises spanning three decades (8401, 9401, and 0701). Symbols in the lower right corner of each plot indicate the median and 20th–80th percentile distributions.

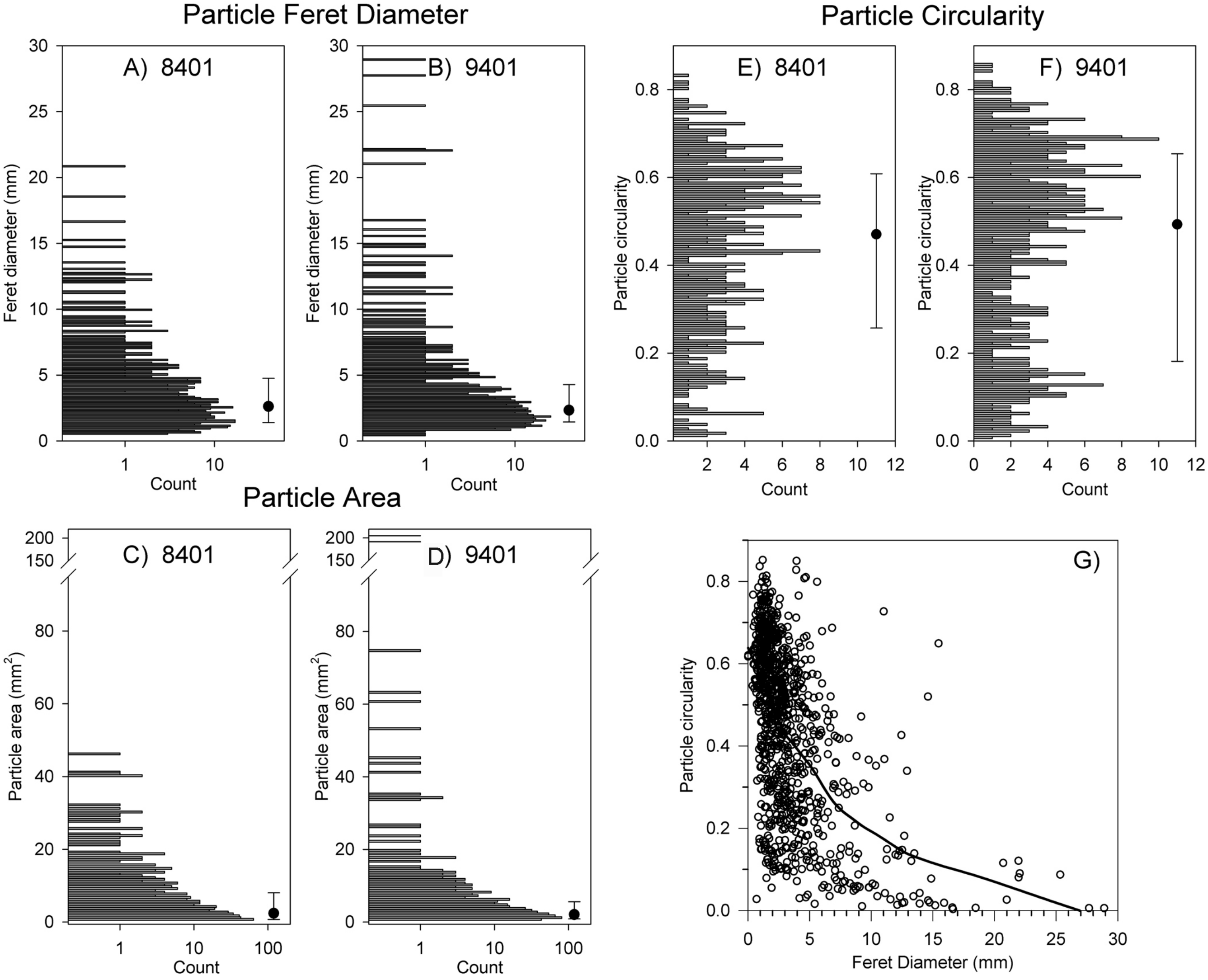

Figure 5. Frequency distributions of (A, B) particle Feret diameter (mm), (C, D) particle surface area (mm^2), and (E, F) particle circularity for the two cruises (8401 and 9401) when plastic particles could be analyzed by ZooScan. Symbols on the right side of each plot indicate the median and 20th–80th percentile distributions. (G) Relationship between particle circularity and particle Feret diameter (mm), for all particles from 8401 and 9401. The solid line describes a fit with a non-parametric Loess smoother (Cleveland and Devlin 1988), with sampling proportion = 0.5.

highly skewed, with most stations showing a small number of particles and a few locations showing appreciably higher concentrations (fig. 4A–C). Median particle concentrations (and 20th and 80th percentile limits of the median; followed by maximum value) in 1984, 1994, and 2007 were 0.011 (0.000–0.077; 0.822), 0.033 (0.000–0.114; 0.909), and 0.016 (0.000–0.059; 3.141) particles/m^3 (fig. 4), respectively. There was no significant difference in particle numerical concentration among cruises (Kruskal-Wallis 1-way ANOVA, $p > 0.20$). The dry mass concentrations were similarly very patchy with medians (20th and 80th percentile limits; maximum): 0.003 (0.000–0.144; 5.337), 0.014 (0.000–0.099; 2.876), and 0.005 (0.000–0.092; 2.305) mg dry mass/m^3 for 1984, 1994, and 2007, respectively (fig. 4D–F). There was no significant difference in particle mass concentration among cruises (Kruskal-Wallis 1-way ANOVA, p > 0.60). The highest dry mass concentration was 5.337 mg/m^3 in winter 1984.

ZooScan optical analysis of individual particles revealed that the median particle Feret diameter (approximately equivalent to particle length) was 2.62 mm on cruise 8401 and 2.33 mm on cruise 9401, with a broad range of sizes in both years (fig. 5A, B). The plastic micro-debris particles also showed a skewed frequency distribution of particle surface area (fig. 5C, D), with a broad tail of particles much larger than the medians (2.42 mm^2 in 8401 and 2.06 mm^2 in 9401). The circularity of the particles was similar on both cruise 8401 (median = 0.470) and cruise 9401 (median = 0.493), with numerous more irregularly shaped particles (fig. 5E, F). None of the measured characteristics (Feret diameter, surface area, and circularity) varied significantly between cruises (Mann-Whitney U test, $p > 0.10$ in all cases). Circularity varied inversely with particle size (Spearman rank correlation = -0.534, $p < 0.00001$), indicating that larger micro-debris particles had more elongate shapes and/or irregular surfaces while progressively smaller particles were consistently more circular (fig. 5G).

DISCUSSION

Results from this study indicate that plastic micro-debris particles are widespread in the surface layer of the ocean in the southern region of the California Current system in winter, and have been present in the area for at least 25 years. Although plastic micro-debris is patchily distributed, 56% to 68% of the stations from throughout the approximately 200,000 km^2 of the sampling domain had detectable plastic debris, including all subregions analyzed.

We detected no significant differences among years in the percentage of stations with plastic micro-debris particles. However, analysis of intervening years would be required to fully assess the magnitude of interannual variability and its relationship to variations in terrestrial sources of plastics, as well as variations in ocean circulation. Thompson et al. (2004) suggested there was an increase in plastic debris particles in plankton samples from waters north of the United Kingdom between the 1960–70s and the 1980–90s.

We detected no trends in particle concentration or particle dry mass distribution over the three decades represented in our study, or in characteristics of the particles analyzed for the two time periods when these could be compared in detail. However, the patchy distribution of these particles in the ocean led to highly skewed frequency distributions. These distributions highlight the importance of a few locations with much higher concentrations, or heavier particles, than the median. Consequently, if there were true underlying trends over time, extensive sampling would be required to resolve them statistically.

It is noteworthy that there was no relationship between the numerical concentration or the dry mass concentration of particles and distance from shore, the presumed source of the majority of debris. We found concentrations of micro-debris in the inshore, intermediate, and offshore regions of the sampling domain. This widespread pattern of occurrence is consistent with the inverse relationship between particle circularity and particle length, as well as declining particle numbers with particle length. Increasing particle circularity with smaller particle size suggests that larger marine debris items with irregular edges become progressively smaller and rounded through time via mechanical breakdown. The dominance of smaller particles in the size spectrum also suggests that the dominant pathway of formation is particle fragmentation (apart from the very small number of intact pre-production plastic pellets detected), and could imply a relatively long residence time in the ocean as small particles accumulate over time. Protracted residence times would lead to greater dispersal by ocean circulation, and thus more geographically widespread micro-debris, as we have observed. Our interpretation of protracted residence time of plastic particles is consistent with Doyle et al.[1]

The average micro-particle size was 2.3–2.6 mm, which is somewhat smaller than the typical diameter of pre-production plastic pellets (3.5 mm). Although a few intact pellets were found, most particles were smaller. In light of passage of smaller particles through the 505 μm mesh sampling net we utilized, it is likely that the true underlying size distribution of micro-debris is skewed even further toward abundant small particles. Although some of the samples we analyzed had been archived for 25 years, the similarity of particle concentrations, length, circularity, and mass distributions in different years of our study suggest there was no particle loss or degradation with time of preservation.

Doyle et al.[1], investigating the distribution and abundance of plastic particles in the southeastern Bering Sea, the CalCOFI region, and further north off the U.S. West Coast from spring 2006 to winter 2007, concluded that a small amount of plastic micro-debris was widely distributed throughout the survey regions. In the Bering Sea, 25% of the spring and 40% of the fall samples contained plastic micro-debris. In the CalCOFI region, the respective percentages were 8.8% in April, 81.2% in July, and 66.7% in October 2006. For all these surface samples, the arithmetic mean of plastic micro-debris mass was less than 0.2 mg/m^3, and the arithmetic mean particle concentration ranged from 0.004 to 0.19/m^3. Subsurface (bongo net) sampling to 210 m depth from spring, summer, and fall 2006 CalCOFI cruises did not yield any plastic micro-debris particles. However, 28% of the subsurface bongo samples collected during January 2007 yielded low mean concentrations and masses of plastic particles.

Doyle et al.[1] compared the mass of plastic micro-debris with zooplankton dry mass and found, on average, the plastic micro-debris mass was 2–3 orders of magnitude lower than zooplankton biomass in the California Current system. We were not able to make such comparisons because displacement volumes or other measures of zooplankton biomass were not available for our samples. It remains to be determined in a quantitative and rigorous manner how California Current system marine micro-debris loads compare with those of the open ocean ecosystem of the North Pacific Central Gyre.

Previous research on plastic debris in the ocean has focused mainly on macro debris, recorded from the poles to the equator (Thompson et al. 2004). Smaller particles have been reported, but they have received far less attention. Carpenter and Smith (1972) reported mean concentrations of 3500 pieces and 290 g/km^2 and concluded that plastic particles were widespread in the western Sargasso Sea. On a multi-ship plankton survey of coastal and oceanic waters from Cape Cod to the Caribbean, Colton et al. (1974) observed a high occurrence of widely distributed plastic particles. The first ship reported a mean concentration of 10.5 g/km^2 for all stations sampled, the second ship 18.1 g/km^2, and the third 77.7 g/km^2.

According to Day and Shaw (1987), the occurrence and abundance of pelagic plastic has been studied less in the North Pacific Ocean and Bering Sea than in the North Atlantic Ocean, Mediterranean Sea, and Caribbean Sea. Day and Shaw (1987) determined the distribution and abundance of pelagic plastics in subtropical and subarctic North Pacific Ocean and Bering Sea waters in 1985 and compared their results with similar observations made in the same areas from 1976 and 1984. They reported great variation, but the mean concentration of small plastics in subtropical waters was around 26 times that in sub-arctic waters and around 400 times that in the Bering Sea. Moore et al. (2001) measured plastics in the North Pacific Central Gyre, recording 27,698 small pieces of plastic with a weight of 424 g from 11 stations. The mean concentration of particles was 334,271 pieces/km^2. Moore et al. (2002) investigated five stations that ran parallel to the southern California coast, collecting during a dry period and also following a rain event. Prior to the storm, the concentration was approximately three pieces/m^3, which is comparable to the maximum value we measured in the present study, while after the rain event, concentrations more than doubled at all stations tested.

Further investigation is needed of the occurrence, distribution, and fate of plastic micro-particles in the California Current system. We suggest that additional analyses be conducted from intervening years, other seasons, and at subsurface depths. We chose to analyze El Niño-neutral years, in order to make the years analyzed from each decade more comparable. However, the relationship between particle distributions and changes in ocean circulation during El Niño-Southern Oscillation are of interest. Also, because manta nets were introduced to CalCOFI only in the late 1970s, it would be informative to analyze subsurface tows that date back to 1949. By using these archived CalCOFI plankton samples, combined with analyses of the chemical characteristics of marine debris and experiments evaluating their effects on planktonic organisms (Arthur et al. 2009), it will be possible to advance our understanding of the history of occurrence and present consequences of marine debris in a major coastal ecosystem.

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APPENDIX TABLE 1

Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
8401	76.7	48	16-Jan-1984	96	0.0000	0.0000			
8401	76.7	51	16-Jan-1984	72	0.1653	0.0138	0.413	10.51	3.97
8401	76.7	55	16-Jan-1984	67	0.0000	0.0000			
8401	76.7	60	16-Jan-1984	107	0.0000	0.0000			
8401	76.7	70	15-Jan-1984	92	1.0012	0.0761	0.255	11.86	5.73
8401	76.7	80	15-Jan-1984	95	0.0000	0.0000			
8401	76.7	90	15-Jan-1984	96	0.0000	0.0000			
8401	76.7	100	15-Jan-1984	85	0.0000	0.0000			
8401	80	51	11-Jan-1984	101	0.0344	0.2970	0.356	9.21	4.84
8401	80	55	12-Jan-1984	81	0.0032	0.0123	0.341	4.56	3.25
8401	80	60	12-Jan-1984	94	0.1114	0.0106	0.331	11.53	4.41
8401	80	60	12-Jan-1984	101	0.0000	0.0792	0.668	0.22	0.66
8401	80	70	13-Jan-1984	91	0.0000	0.0000			
8401	80	70	13-Jan-1984	93	0.0000	0.0000			
8401	80	80	14-Jan-1984	85	0.0019	0.0118	0.330	2.09	2.49
8401	80	90	14-Jan-1984	100	0.0057	0.0200	0.472	5.17	3.48
8401	80	100	14-Jan-1984	86	0.1902	0.3721	0.498	4.56	3.17
8401	82	46	10-Jan-1984	82	0.0000	0.0000			
8401	83.3	40.6	10-Jan-1984	96	0.0248	0.0417	0.411	21.16	3.58
8401	83.3	42	10-Jan-1984	87	0.0000	0.0000			
8401	83.3	51	10-Jan-1984	85	0.0000	0.0000			
8401	83.3	55	10-Jan-1984	84	0.0000	0.0000			
8401	83.3	60	10-Jan-1984	80	0.0000	0.0000			
8401	83.3	70	9-Jan-1984	99	0.0000	0.0000			
8401	83.3	80	9-Jan-1984	91	0.2371	0.0549	0.505	6.55	3.66
8401	83.3	90	9-Jan-1984	94	0.0348	0.0106	0.441	4.49	3.09
8401	83.3	100	8-Jan-1984	79	0.2158	0.4810	0.417	2.62	3.60
8401	83.3	100	8-Jan-1984	93	0.4454	0.1290	0.476	2.58	3.49
8401	86.7	33	5-Jan-1984	116	0.1303	0.1207	0.439	10.25	4.81
8401	86.7	35	5-Jan-1984	122	5.3366	0.0410	0.032	4.93	13.38
8401	86.7	40	5-Jan-1984	90	0.0027	0.0222	0.384	0.86	1.94
8401	86.7	45	5-Jan-1984	80	0.0000	0.0000			
8401	86.7	50	6-Jan-1984	89	0.0000	0.0000			
8401	86.7	55	6-Jan-1984	104	0.0000	0.0000			
8401	86.7	60	6-Jan-1984	92	0.0027	0.0217	0.412	1.27	1.85
8401	86.7	70	7-Jan-1984	90	0.0150	0.0333	0.303	3.66	3.82
8401	86.7	80	7-Jan-1984	94	0.0291	0.0745	0.410	2.45	3.50
8401	86.7	90	7-Jan-1984	96	0.0077	0.0208	0.321	5.54	4.66
8401	86.7	100	7-Jan-1984	85	0.1768	0.4706	0.462	2.77	2.13
8401	90	28	5-Jan-1984	90	0.1592	0.5333	0.507	1.45	1.82
8401	90	30	5-Jan-1984	101	1.1132	0.8218	0.379	7.04	3.99
8401	90	35	4-Jan-1984	109	0.0347	0.0275	0.242	16.99	5.15
8401	90	37	5-Jan-1984	107	0.7887	0.2243	0.460	6.35	3.47
8401	90	53	5-Jan-1984	104	0.0000	0.0000			
8401	90	60	7-Jan-1984	78	0.0000	0.0000			
8401	90	70	7-Jan-1984	96	0.0000	0.0000			
8401	90	80	8-Jan-1984	85	5.1880	0.1059	0.475	25.01	7.23
8401	90	90	8-Jan-1984	92	0.0199	0.0652	0.570	2.26	2.16
8401	90	100	8-Jan-1984	98	0.0973	0.0918	0.335	4.05	3.25
8401	93.3	26.7	12-Jan-1984	96	0.0015	0.0104	0.057	2.43	9.06
8401	93.3	29	12-Jan-1984	82	0.0565	0.0366	0.529	2.50	2.11
8401	93.3	30	11-Jan-1984	59	0.1276	0.0678	0.350	6.30	5.18
8401	93.3	35	10-Jan-1984	90	0.0000	0.0000			

APPENDIX TABLE 1 (continued)
Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
8401	93.3	40	10-Jan-1984	129	0.1382	0.0078	0.308	23.05	9.38
8401	93.3	45	10-Jan-1984	109	0.0000	0.0000			
8401	93.3	50	10-Jan-1984	119	0.0000	0.0000			
8401	93.3	60	10-Jan-1984	119	0.0000	0.0000			
8401	93.3	70	9-Jan-1984	122	0.0000	0.0000			
8401	93.3	80	9-Jan-1984	70	0.0000	0.0000			
8401	93.3	90	9-Jan-1984	84	0.0000	0.0000			
8401	93.3	100	9-Jan-1984	107	0.0556	0.0374	0.373	5.65	4.70
9401	76.7	49	5-Feb-1994	104	0.0072	0.0577	0.341	4.30	3.35
9401	76.7	51	5-Feb-1994	97	0.0000	0.0000			
9401	76.7	55	5-Feb-1994	88	0.0000	0.0000			
9401	76.7	60	5-Feb-1994	87	0.0000	0.0000			
9401	76.7	70	5-Feb-1994	96	0.6702	0.7396	0.468	3.70	2.98
9401	76.7	80	4-Feb-1994	103	0.0241	0.0485	0.330	3.41	2.70
9401	76.7	90	4-Feb-1994	81	0.0021	0.0617	0.511	0.57	1.08
9401	76.7	100	4-Feb-1994	91	0.0000	0.0000			
9401	80	51	2-Feb-1994	92	0.5308	0.0543	0.362	4.21	2.72
9401	80	55	2-Feb-1994	92	0.0000	0.0000			
9401	80	60	3-Feb-1994	101	0.0138	0.0198	0.265	2.45	8.45
9401	80	70	3-Feb-1994	89	0.0147	0.0337	0.294	3.13	6.39
9401	80	80	3-Feb-1994	99	0.0196	0.0505	0.330	3.29	3.74
9401	80	90	3-Feb-1994	81	0.3064	0.0741	0.306	3.85	5.08
9401	80	100	4-Feb-1994	82	0.0013	0.0122	0.004	5.88	16.64
9401	81.8	46.9	2-Feb-1994	102	0.0000	0.0000			
9401	83.3	40.6	2-Feb-1994	94	0.2306	0.0106	0.711	10.69	3.92
9401	83.3	42	2-Feb-1994	95	0.0000	0.0000			
9401	83.3	51	1-Feb-1994	88	0.0000	0.0000			
9401	83.3	55	1-Feb-1994	94	0.0000	0.0000			
9401	83.3	60	1-Feb-1994	86	0.0000	0.0000			
9401	83.3	70	1-Feb-1994	97	0.0455	0.0412	0.491	2.91	2.26
9401	83.3	80	31-Jan-1994	89	0.2011	0.2247	0.407	6.10	5.27
9401	83.3	90	31-Jan-1994	102	0.3133	0.3922	0.519	2.69	3.16
9401	83.3	100	31-Jan-1994	89	0.0109	0.0225	0.314	5.67	14.91
9401	83.3	110	30-Jan-1994	86	0.0000	0.0116	0.027	4.05	11.57
9401	86.7	33	27-Jan-1994	89	0.3157	0.1573	0.476	35.10	7.33
9401	86.7	35	28-Jan-1994	106	0.2028	0.0849	0.314	5.67	14.91
9401	86.7	40	28-Jan-1994	97	0.0466	0.0515	0.597	2.13	1.98
9401	86.7	45	28-Jan-1994	99	0.2104	0.0404	0.219	7.06	4.12
9401	86.7	50	28-Jan-1994	87	0.0077	0.0230	0.619	0.02	0.02
9401	86.7	55	28-Jan-1994	99	0.0046	0.0202	0.631	0.68	1.19
9401	86.7	60	29-Jan-1994	99	0.7794	0.9090	0.335	3.14	2.57
9401	86.7	70	29-Jan-1994	86	0.0422	0.1860	0.474	2.54	2.46
9401	86.7	80	29-Jan-1994	91	0.0491	0.0989	0.505	4.35	2.64
9401	86.7	90	30-Jan-1994	94	0.0537	0.0319	0.355	0.93	2.07
9401	86.7	100	30-Jan-1994	88	0.0300	0.0454	0.423	2.39	3.13
9401	86.7	110	30-Jan-1994	90	0.0841	0.1111	0.449	2.38	3.26
9401	90	28	27-Jan-1994	87	0.0000	0.0000			
9401	90	30	27-Jan-1994	91	0.0312	0.0110	0.477	8.27	4.93
9401	90	35	27-Jan-1994	88	0.0000	0.0000			
9401	90	37	27-Jan-1994	87	0.0000	0.0000			
9401	90	45	26-Jan-1994	92	0.0000	0.0000			
9401	90	53	26-Jan-1994	88	0.0000	0.0000			
9401	90	60	26-Jan-1994	82	0.0000	0.0000			
9401	90	70	26-Jan-1994	91	0.0000	0.0000			
9401	90	80	25-Jan-1994	77	0.0000	0.0000			
9401	90	90	25-Jan-1994	84	0.0000	0.0000			
9401	90	100	25-Jan-1994	93	0.0088	0.0175	0.465	1.88	2.38
9401	90	110	24-Jan-1994	79	0.0000	0.0000			
9401	90	120	24-Jan-1994	94	0.0182	0.0106	0.019	12.01	15.91
9401	93.3	26.7	20-Jan-1994	99	2.8765	0.3636	0.504	14.27	5.26
9401	93.3	28	20-Jan-1994	93	0.0891	0.0645	0.408	8.83	4.03
9401	93.3	30	20-Jan-1994	91	0.2387	0.4066	0.492	2.58	2.24
9401	93.3	35	21-Jan-1994	93	0.1229	0.5380	0.518	2.51	5.46

APPENDIX TABLE 1 (continued)
Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
9401	93.3	40	21-Jan-1994	85	0.0061	0.0353	0.380	12.51	6.03
9401	93.3	45	21-Jan-1994	91	0.0490	0.0549	0.418	3.25	2.43
9401	93.3	50	21-Jan-1994	86	0.0000	0.0000			
9401	93.3	55	21-Jan-1994	88	0.0094	0.0341	0.125	3.25	7.22
9401	93.3	60	22-Jan-1994	93	0.0223	0.0538	0.542	4.12	2.84
9401	93.3	70	22-Jan-1994	90	0.0456	0.1222	0.560	2.30	2.25
9401	93.3	80	22-Jan-1994	100	0.0297	0.1200	0.479	1.61	2.34
9401	93.3	90	23-Jan-1994	99	0.0397	0.1212	0.533	1.65	2.13
9401	93.3	100	23-Jan-1994	89	0.0279	0.1011	0.435	1.73	2.34
9401	93.3	110	23-Jan-1994	91	0.0651	0.1648	0.430	3.55	3.11
9401	93.3	120	24-Jan-1994	98	0.0088	0.0204	0.542	1.00	1.73
0701	76.7	49	28-Jan-2007	79	0.0000	0.0000			
0701	76.7	51	28-Jan-2007	73	0.0550	0.0550			
0701	76.7	55	28-Jan-2007	57	0.0000	0.0000			
0701	76.7	60	29-Jan-2007	69	0.3444	0.1592			
0701	76.7	70	29-Jan-2007	72	2.3049	0.2083			
0701	76.7	80	29-Jan-2007	78	0.0205	0.0513			
0701	76.7	90	29-Jan-2007	71	0.0865	0.0141			
0701	76.7	100	29-Jan-2007	75	0.2019	0.6818			
0701	80	51	28-Jan-2007	76	0.0000	0.0000			
0701	80	55	28-Jan-2007	70	0.0313	0.0284			
0701	80	60	27-Jan-2007	56	0.0063	0.0179			
0701	80	70	27-Jan-2007	69	0.0491	0.0723			
0701	80	80	27-Jan-2007	65	0.0011	0.0154			
0701	80	90	27-Jan-2007	67	0.0404	0.0299			
0701	80	100	26-Jan-2007	65	0.1972	0.0308			
0701	81.8	46.9	24-Jan-2007	90	0.1573	0.0332			
0701	83.3	40.6	24-Jan-2007	82	0.2866	0.0366			
0701	83.3	42	24-Jan-2007	80	0.0038	0.0125			
0701	83.3	51	24-Jan-2007	66	0.0000	0.0000			
0701	83.3	55	25-Jan-2007	68	0.0000	0.0000			
0701	83.3	60	25-Jan-2007	46	0.0000	0.0000			
0701	83.3	70	25-Jan-2007	67	0.1040	0.0594			
0701	83.3	80	25-Jan-2007	57	0.0005	0.0175			
0701	83.3	90	26-Jan-2007	70	0.0459	0.0717			
0701	83.3	100	26-Jan-2007	64	0.0027	0.0156			
0701	83.3	110	26-Jan-2007	75	0.3720	0.6133			
0701	86.7	33	23-Jan-2007	69	0.0193	0.0290			
0701	86.7	35	23-Jan-2007	66	1.5129	0.6393			
0701	86.7	40	23-Jan-2007	65	0.0000	0.0000			
0701	86.7	45	23-Jan-2007	68	0.1467	0.0593			
0701	86.7	50	23-Jan-2007	64	0.0000	0.0000			
0701	86.7	55	23-Jan-2007	66	0.0198	0.0152			
0701	86.7	60	22-Jan-2007	65	0.0048	0.0154			
0701	86.7	70	22-Jan-2007	61	0.0048	0.0659			
0701	86.7	80	22-Jan-2007	69	0.0000	0.0000			
0701	86.7	90	22-Jan-2007	62	0.0048	0.0160			
0701	86.7	100	21-Jan-2007	59	0.0000	0.0000			
0701	86.7	110	21-Jan-2007	70	0.0742	0.2282			
0701	90	28	18-Jan-2007	64	0.0055	0.0156			
0701	90	30	18-Jan-2007	64	0.0406	0.1250			
0701	90	35	18-Jan-2007	60	0.0103	0.0167			
0701	90	37	18-Jan-2007	66	0.0008	0.0152			
0701	90	45	18-Jan-2007	64	0.0125	0.0156			
0701	90	53	19-Jan-2007	58	0.0009	0.0174			
0701	90	60	19-Jan-2007	59	0.0000	0.0000			
0701	90	70	19-Jan-2007	59	0.0118	0.0508			
0701	90	80	20-Jan-2007	60	0.0000	0.0000			
0701	90	90	20-Jan-2007	70	0.0000	0.0000			
0701	90	100	20-Jan-2007	54	0.0000	0.0000			
0701	90	110	21-Jan-2007	70	0.0007	0.0143			
0701	90	120	16-Jan-2007	66	0.0000	0.0000			
0701	93.3	26.7	12-Jan-2007	58	0.0000	0.0000			

APPENDIX TABLE 1 (continued)

Concentration of plastic micro-debris particles on cruises 8401, 9401, and 0701, together with average physical characteristics of plastic particles on cruises 8401 and 9401.

Cruise	Line	Sta.	Date	Volume filtered (m^3)	Mass conc. (mg/m^3)	Numerical conc. ($No./m^3$)	Median Circularity	Mean Surf. Area (mm^2)	Mean Feret Diam. (mm)
0701	93.3	28	13-Jan-2007	59	1.6112	3.1409			
0701	93.3	30	13-Jan-2007	71	2.1591	0.5390			
0701	93.3	35	13-Jan-2007	60	0.0000	0.0000			
0701	93.3	40	13-Jan-2007	60	0.0000	0.0000			
0701	93.3	45	13-Jan-2007	61	0.0000	0.0000			
0701	93.3	50	14-Jan-2007	58	0.2363	0.0342			
0701	93.3	55	14-Jan-2007	66	0.0000	0.0000			
0701	93.3	60	14-Jan-2007	62	0.0421	0.0324			
0701	93.3	70	14-Jan-2007	63	0.0000	0.0000			
0701	93.3	80	14-Jan-2007	56	0.0018	0.0540			
0701	93.3	90	15-Jan-2007	57	0.0000	0.0000			
0701	93.3	100	15-Jan-2007	62	0.0000	0.0000			
0701	93.3	110	15-Jan-2007	70	0.0000	0.0000			
0701	93.3	120	16-Jan-2007	56	0.0323	0.0179			

SMALL PELAGIC FISH CATCHES IN THE GULF OF CALIFORNIA ASSOCIATED WITH SEA SURFACE TEMPERATURE AND CHLOROPHYLL

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ABSTRACT

The Gulf of California supports an important fishery of small pelagic fishes. However, these species have undergone variations in both their geographic distribution and abundance over time. A GIS-based approach was used to investigate the association between weekly remote-sensed sea surface chlorophyll-a concentrations (Chl), sea surface temperature (SST) images, derived SST and Chl gradient maps, and daily fisheries catch data for Pacific sardine (*Sardinops sagax caeruleus*), thread herring (*Opisthonema libertate*), northern anchovy (*Engraulis mordax*), and Pacific mackerel (*Scomber japonicus*) from 2002–07. SST did not have a significant affect on most species, except for northern anchovy ($r^2 = 0.71$), while Chl was significant for Pacific sardine ($r^2 = 0.94$), thread herring ($r^2 = 0.90$), and Pacific mackerel ($r^2 = 0.96$). However, the SST gradient was more strongly associated with the abundance of the species studied. The Chl gradients showed similar values in relation to SST gradients with the exception of northern anchovy ($r^2 = 0.43$).

INTRODUCTION

The Gulf of California (GC) supports an important fishing industry of small pelagic fishes (Cisneros-Mata et al. 1995). This fishery is multispecific and includes eight species, although the Pacific sardine (*Sardinops sagax*) is the most dominant (about 80% of the total landings; Nevárez-Martínez et al. 2001). Small pelagic fishes have undergone considerable variations in both their distribution and abundance over time (Lluch-Belda et al. 1986; Lluch-Belda et al. 1989; Nevárez-Martínez et al. 2001) (fig. 1) influenced by variations in the ocean climate (Lluch-Belda et al. 1989; Bakun and Broad 2003; deYoung et al. 2004).

Due to the spatio-temporal nature of fisheries data, the use of spatial tools such as GIS is an essential factor in sustainable fisheries management. GIS combined with other tools such as remote sensing images can make fisheries management more efficient, since they can provide comprehensive tools, image comparison and processing functions for environmental monitoring and mapping.

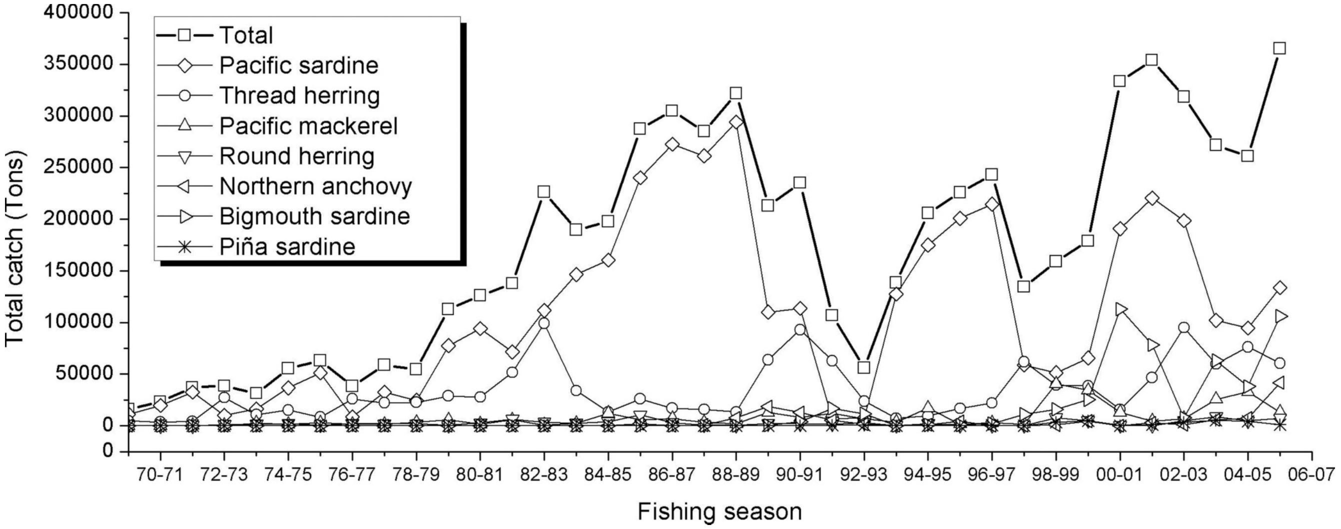

Figure 1. Total catch of Small pelagic fisheries for Pacific sardine (*Sardinops sagax*), thread herring (*Opisthonema libertate*), Pacific mackerel (*Scomber japonicus*), round herring (*Etremeus teres*), northern anchovy (*Engraulis mordax*), bigmouth sardine (*Cetengraulis mysticetus*), and piña sardine (*Oligoplites refulgens*) in the Gulf of California,1969–2006 (from Nevárez-Martínez et al. 2001).

This has been shown in other fields where spatially-related problems occur (Curtis 1999). Remote-sensed SST images and GIS tools have been widely applied to spatially relating fisheries and environmental features in the ocean (e.g., Fernández and Pingree 1996; Santos 2000). These applications have focused mainly on the Pacific sardine, northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*; Perrotta et al. 2001; Bava et al. 2002) with the use of mapping tools such as GIS (Yáñez et al. 2004). These studies showed that SST significantly affects jack mackerel distribution (Perrotta et al. 2001). Also, some SST-derived products, such as SST gradients (which detect fronts as indirect indicators of fishing-ground regions), have been used to relate oceanographic conditions and species distribution (Yáñez et al. 2004), such as for Atlantic herring (*Clupea harengus*) in the northern North Sea (Maravelias and Reid 1995), Peruvian anchovy (*Engraulis ringens*) and Pacific sardine off the coast of Chile (Castillo et al. 1996), and European pilchard (*Sardina pilchardus*) and European anchovy (*Engraulis encrasicolus*) in the northern Aegean Sea (Giannoulaki et al. 2005). These studies generally illustrated low correlation between species distribution and SST, so these species may be more directly related to plankton concentration. Other studies have looked at the associations between high plankton concentrations and fish distribution such as for Atlantic herring in the northern North Sea (Maravelias and Reid 1995) and northern anchovy in the eastern Pacific Ocean (Robinson 2004).

There are many studies relating abundance, composition, and variability of small pelagic fishes in the GC to environmental conditions (Lluch-Belda et al. 1986; Hammann et al. 1988; Lluch-Belda et al. 1991; Cisneros-Mata et al. 1996; Lluch-Cota et al. 1999; Nevárez-Martínez et al. 2001). A growing body of evidence suggests that environmental factors play a dominant role in the seasonality of small pelagic fishes; Lluch-Belda et al. 1986 observed that during an El Niño-Southern Oscillation (ENSO) event, catches of thread herring and Pacific sardine vary inversely in the Gulf of California. Recent studies on the distribution and abundance of pelagic fishes also use spatial information (Nevárez-Martínez et al. 2001; Lanz et al. 2008). For example, Nevárez-Martínez et al. 2001 analyzed the distribution and the abundance of the Pacific sardine off the Gulf of California in relation to wind patterns (upwelling) and sea surface temperature. The results showed that the highest abundance of Pacific sardine was related to moderate upwelling (13–18 m^3/s per 10 m of coastline) and sea surface temperatures of 19° to 25°C.

Species and Study Area

A variety of species of small pelagic fishes are present in the Gulf of California waters. They include Pacific sardine (*Sardinops sagax caeruleus*), northern anchovy, thread herring (*Opisthonema libertate*), Pacific mackerel, bigmouth sardine (*Cetengraulis mysticetus*) round herring (*Etremeus teres*) and Piña sardine (*Oligoplites refulgens*) (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 2001). Although all of these species are caught by commercial fisheries, Pacific sardine and northern anchovy have traditionally been the most economically important (Cisneros-Mata et al. 1995; Nevárez-Martínez et al. 2001), and therefore the main focus of scientific studies.

The study area consists of the entire Gulf of California (fig. 2). The GC's high productivity is well documented (Alvarez-Borrego 1983; Santamaría-del-Angel et al. 1994) and caused by a combination of bottom topography and a high degree of wind-induced mixing and upwelling from strong predominantly north-westerly winds particularly in the midriff islands region (Alvarez-Borrego 1983; Pegau et al. 2002). The area is becoming an important spawning area for anchovy and sardine (Lluch-Belda et al. 1991; Cisneros-Mata et al. 1996). Ocean circulation in the GC is determined mainly by the tide and winds. Residual currents in the GC are responsible for the net transport of substances (Lavin et al. 1997). Satellite measurements of sea surface temperature and ocean color have been used to study the circulation in the Gulf of California (Badan-Dangon et al. 1985; Paden et al. 1991; Lavin et al. 1997) and to provide an understanding of the biological production in the GC (Gaxiola-Castro et al. 1999). Recent studies in the GC describe the existence of small areas where biological activity is particularly high, and which have been used to regionalize the GC based on several levels of primary productivity (Santamaría-del-Ángel et al. 1994; Lluch-Cota and Arias-Aréchiga 2000). These regions, named "Biological Action Centers" (BACs), appear to be fixed in space, tied to coastal features, and tend to show little seasonal variation in productivity level. Small pelagic fish prefer these areas and commercial species aggregate in them (Lluch-Cota and Arias-Aréchiga 2000; Lluch-Belda et al. 2003a). Similar productivity patterns in the GC have been observed by Pegau et al. 2002 based on SST and Chl images from satellites that show a series of eddies with alternating directions of rotation, and suggest that the eddies are topographically locked.

Due to its high productivity, the GC supports important commercial fisheries, mainly small pelagic fishes. Small pelagic fisheries in the GC are exploited by a specialized fleet of purse-seiners, with hold capacities of between 125 and 180 t. We used the small pelagic fishery catch data from the commercial fleet for this study.

This paper describes the relationship of the commercial fishing activity in the GC and weekly remote-sensed oceanographic conditions images, particularly SST, Chl and derived SST and Chl gradients, from 2002

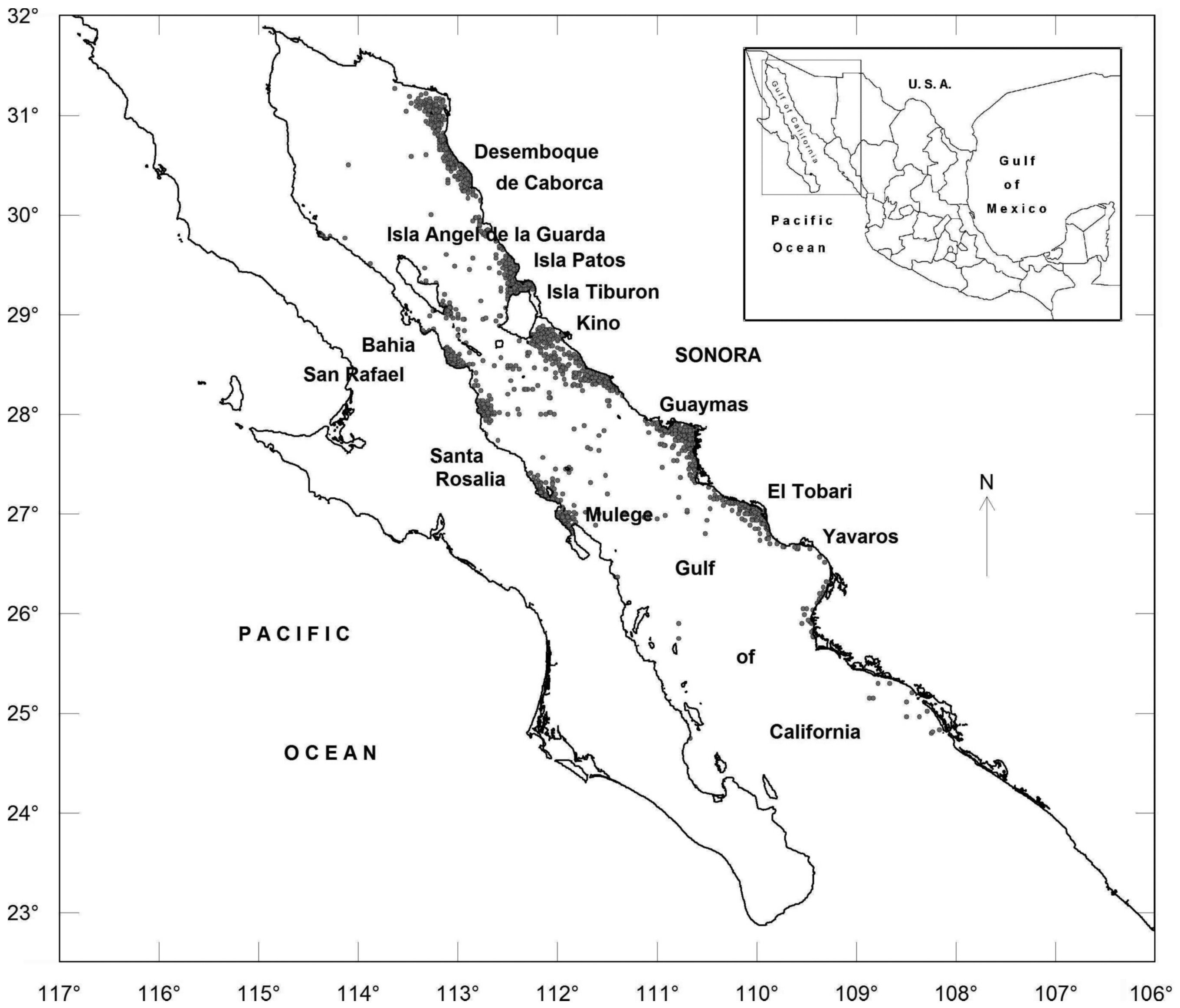

Figure 2. Location of the study area showing the catch distribution (dark grey points) of the Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), thread herring (*Opisthonema libertate*), and northern anchovy (*Engraulis mordax*) small pelagic fishery in the Gulf of California, 2002–07.

to 2007 using GIS based on the spatial distribution of fisheries data in order to get a reliable vision of the fishing grounds location especially on a small scale. This information is important to sustainable management.

MATERIALS AND METHODS

Fisheries Data

We converted the commercial fishing logbook data from 2002 to 2007 in the study area with date, geographic position, total catch, and species composition to a spatial database. In order to overlay both fisheries data and satellite images and create individual point maps in a GIS environment, a georeference within a coordinate system that contains projection information was created and applied to all fishery data.

Satellite Data and Derived Maps

Global eight-day SST and Chl composites (mean) products derived from MODIS (MODerate resolution Imaging Spectroradiometer) sensor onboard the Aqua satellite from 2002 to 2007 were downloaded via the internet from http://daac.gsfc.nasa.gov/data. This data set consists of satellite measurements of global ocean color and sea surface temperature (SST) data obtained by MODIS in orbit on the Aqua (formerly EOS PM) platform. MODIS ocean color and SST products are processed and distributed by the Ocean Biology Processing Group (OBPG). MODIS Aqua processing details can be found at http://oceancolor.gsfc.nasa.gov/DOCS/MODISA_processing.html. The data were taken in L3 mapped and HDF format in 4 km ground resolution and further imported into a GIS environment. SST images corresponded to 11µ nighttime SST and Chlorophyll-a concentrations were computed using the linear (Equation 1) and logarithmic (Equation 2) scaling equations, respectively:

$$SST\_value = (Slope{*}l3m\_data) + Intercept), \tag{1}$$

$$Chl\_value = Base^{((Slope{*}l3m\_data) + Intercept)}, \tag{2}$$

where *SST_value* and *Chl_value* are the remote-sensed retrieved SST (°C) or Chl (mg/m^3) values, respectively; the *Slope* value depends on the parameter: For SST, the value is 7.1785×10^{-4} and, for Chl the value is equal to 5.81378×10^{-5}. The parameter *l3m_data* is the raw value in byte of the image, and *Intercept* value is equal to -2.0 in both equations.

Sub-maps of the weekly SST and Chl images for the study area were created for each fishing season, which represent a matrix of 228 lines and 240 columns. Additionally, SST and Chl-gradient (GSST and GChl) images were obtained from each selected weekly SST and Chl composites by applying Sobel operators in 3 × 3 kernels. The Sobel filter consists of two kernels that detect horizontal and vertical changes in an image. If both are applied to an image, the results can be used to approximate the magnitude of the edges in the image as follows:

$$G_{horizontal} = \begin{vmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{vmatrix}, \tag{3}$$

$$G_{vertical} = \begin{vmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{vmatrix}, \tag{4}$$

$$Magnitude_{Sobel} = \sqrt{G^2_{horizontal} + G^2_{vertical}}, \tag{5}$$

where $G_{horizontal}$ and $G_{vertical}$ are two images which, at each point, contain the horizontal (x) and vertical (y) derivative approximations. The x-coordinate increases in the "right"-direction, and the y-coordinate increases in the "down" direction. $Magnitude_{Sobel}$ is the resulting gradient approximation at each point in the image.

GIS Mapping

To explore the association of each species with remote-sensed SST and Chl, individual point maps were produced to visualize the CPUE (catch per unit of effort) values throughout the study area. These point maps were further re-sampled into a regular grid with 4 km spatial resolution to produce raster maps in order to match the spatial resolution of the fishery and satellite information.

The weekly CPUE values, in terms of tons by landing, were mapped to produce point density (mean) covers of fisheries records (point maps) by re-sampling individual records in the selected grid and by averaging the CPUE values falling in each individual cell, and further combining them with environmental (SST, Chl and gradients) maps to extract environmental values for each fishery (Pacific sardine, chub mackerel, northern anchovy and thread herring). Cells that contained no information were assigned a null attribute.

Statistical Approach

A frequency distribution analysis for each individual species was computed against each environmental parameter in order to study the associations between the fisheries data and the satellite information. A set of probabilistic distributions, both Gaussian (Equation 6) and logarithmic (Equation 7), were applied to the frequency analysis to determine the best-fit functions based on a Pearson's chi-square goodness-of-fit test (Equation 8), with a confidence level for curves of 95%. To find parameter estimates and make nonlinear curves fit parameter values for each non-linear function, an iterative process was used.

Gaussian Fit:

$$y = y_0 + \frac{A}{w\sqrt{\pi/2}}\, e^{-2\frac{(x - x_c)^2}{w^2}}, \tag{6}$$

Log-Normal Fit:

$$y = y_0 + \frac{A}{\sqrt{2\pi w x}}\, e^{-\left[\frac{\ln \frac{x}{xc}}{2w^2}\right]^2}, \tag{7}$$

where y is the output value of the probability function; y_0 is the offset of the estimated parameter; x_c is the center; w is the width of the function, and A is the area. The "best fit" nonlinear model using chi-square was computed as:

$$X^2 = \sum_{i=1}^{n} w_i * (y_i - \hat{y})^2, \tag{8}$$

where: X^2 is the chi-square parameter value; w_i is the weighted coefficient, y_i is the experimental data point

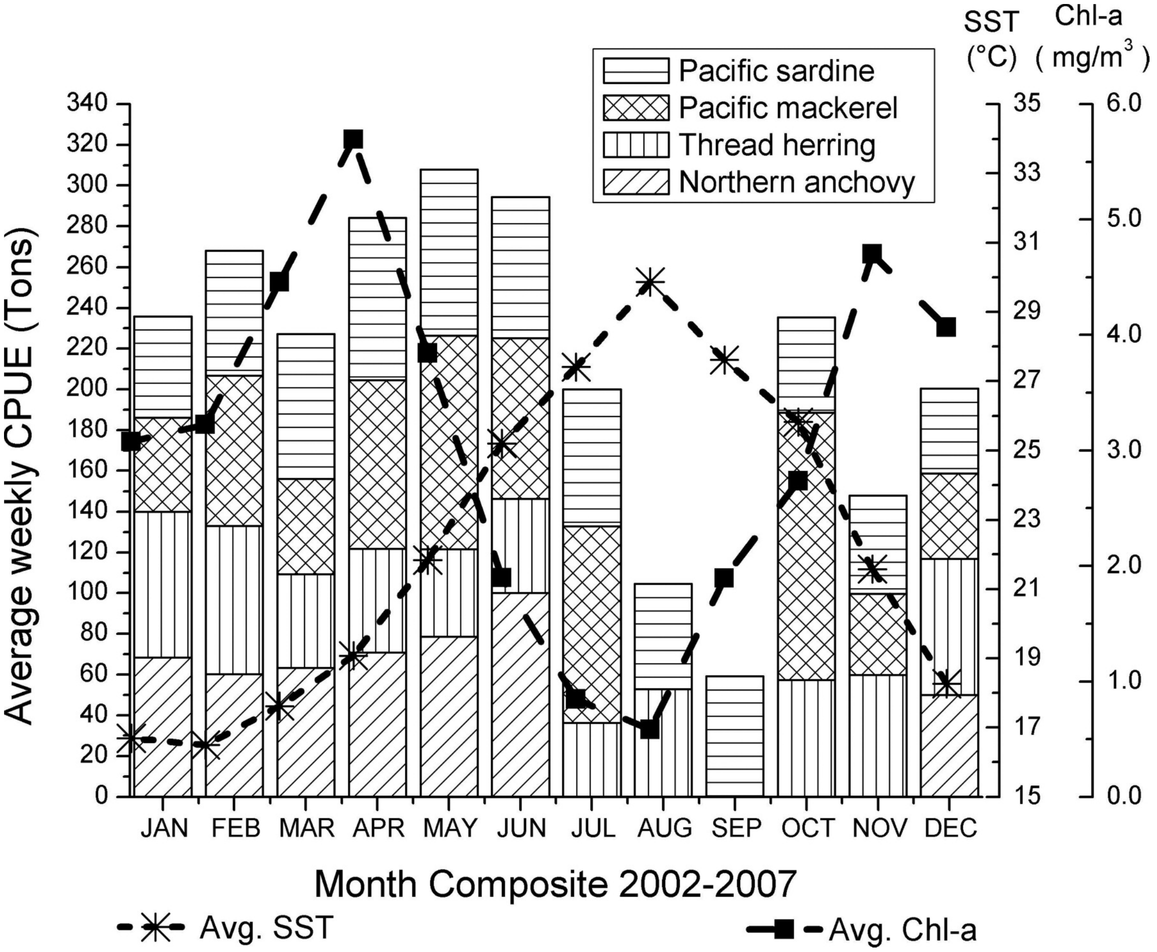

Figure 3. Mean monthly remote sensed sea surface temperature, Chlorophyll-*a* concentration and pelagic fish landings in the Gulf of California from 2002–07.

and *y* is the theoretical point. Our goal was to obtain the "best-fit" parameter values by minimizing chi-square.

RESULTS

Fisheries Data Distribution

A total of 1,842 of individual records, ranging from October 2002 to June 2007 were extracted from logbooks in the study area and matched with the environmental variables and derived maps. The spatial scatter plots (fig. 2) and the point density (not shown) maps of fishing sets show a wide distribution. The setting density map (not shown) has a range of cell values from 1 to 81, while the catch-density map has a range from 5 to 4,255.

Temporal Patterns of Satellite-Inferred SST and Chl *a*

A total of 143 weekly composites were selected from each SST and Chl image that matched the fisheries data. A comparison between monthly-averaged SST and monthly-averaged Chl concentrations (fig. 3) calculated using the satellite data for the period 2002 to 2007 had an inverse relationship. The highest monthly-averaged SST values (>25°C) were found between July and October, and the highest concentrations of Chl or blooms (>3 mg/m^3) were found during the colder months (November–May), and decreased (<1 mg/m^3) during the summer months. The observed blooms may be related to physical oceanographic features such as monsoon-causing coastal upwellings (Lavin et al. 1997; Lluch-Cota 2000; Pegau et al. 2002).

Environmental Impacts on the Abundance of Small Pelagic Fishes

For each CPUE data point, the SST, Chl concentration and derived gradient maps were extracted from the corresponding weekly composite.

Frequency analyses for the oceanographic parameters and abundances of small pelagic fishes in the GC are shown in Figure 4. Figure 4 also shows the best-fit function (Gaussian or log normal) based on a Chi-square test

TABLE 1
SST probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi^2	*R*^{2}	Interval (°C)	Optimal range (°C)
Pacific sardine	1 222	LogNormal	759.91	0.700	14.5–31.6	17.0–22.0
Thread herring	348	Gauss	66.55	0.485	15.7–30.1	17.0–21.0
Pacific mackerel	143	Gauss	20.78	0.480	16.5–28.8	25.0–29.0
Northern anchovy	129	Gauss	20.00	0.710	15.7–23.1	17.0–22.0

TABLE 2
Chl probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi^2	*R*^{2}	Interval (mg/m^3)	Optimal range (mg/m^3)
Pacific sardine	1 146	LogNormal	205.68	0.937	0.57–10.7	1.0–3.0
Thread herring	342	LogNormal	31.92	0.897	0.42–9.91	1.0–3.5
Pacific mackerel	134	LogNormal	5.526	0.959	0.45–5.60	1.0–1.5
Northern anchovy	111	Gauss	3.523	0.573	0.79–25.45	2.5–4.5

TABLE 3
Sobel SST gradient probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi^2	*R*^{2}	Interval (°C/km)	Optimal range (°C/km)
Pacific sardine	1 214	LogNormal	189.76	0.969	0.32–6.51	1.0–2.5
Thread herring	352	LogNormal	32.75	0.936	0.44–4.80	1.0–3.0
Pacific mackerel	142	LogNormal	2.42	0.967	0.22–6.00	1.0–2.5
Northern anchovy	132	LogNormal	4.14	0.865	0.50–7.21	1.0–4.0

TABLE 4
Sobel Chl gradient probability distributions for the small pelagic species in the Gulf of California, statistical parameters and optimal values, estimated for the period 2002–07.

Species	*N*	Distribution	Reduced Chi^2	*R*^{2}	Interval (mg/m^3/km)	Optimal range (mg/m^3/km)
Pacific sardine	998	Gauss	61.34	0.955	0.36–29.32	0.5–5.0
Thread herring	318	LogNormal	5.85	0.961	0.50–34.06	2.0–6.0
Pacific mackerel	125	Gauss	2.52	0.966	0.22–14.22	0.5–2.5
Northern anchovy	92	LogNormal	3.69	0.434	1.94–67.14	3.0–17.0

with the 95% confidence limits. Table 1 through Table 4 show mean values for the variables considered in the analysis (SST, Chl, GSST [Gaussian SST], and GChl [Gaussian Chl]) for the best-fit function.

DISCUSSION

Frequency distributions of fisheries data provided a comprehensive analysis of the fishery and its relationship with environmental variables, such as SST and Chl, which can complement traditional time-series analyses in strategic management. In the GC, small pelagic fish distributions respond to a combination of biotic and abiotic factors. For Pacific sardine, Lluch-Belda et al. 1995 proposed the existence of two distribution centers: (a) the Gulf of California surrounding the Great Islands, and (b) the Pacific Ocean, Punta Eugenia west of Baja California. From these centers, populations of sardine expand and contract for feeding or spawning, following unknown environmental factors. Generally, Pacific sardine concentrate in the north-central coast of the GC (Isla Patos and south of Isla Angel de la Guarda), and thread herring along the south-central coast (Sonora and north of Sinaloa; Nevárez-Martínez et al. 2003). Figure 2 shows a wide spatial distribution of small pelagic fishes in the Gulf of California, concentrated in the Great Islands; this is similar to the findings of Lluch-Belda et al. 1995.

Analyses of fishing data time series for the fishing seasons 2002 to 2007 (fig. 3) suggest that the highly seasonal nature of the fishery is associated with seasonal changes in temperature and chlorophyll. The normalized data structure from Figure 3 in the form of CPUE anomalies compared to average monthly composites

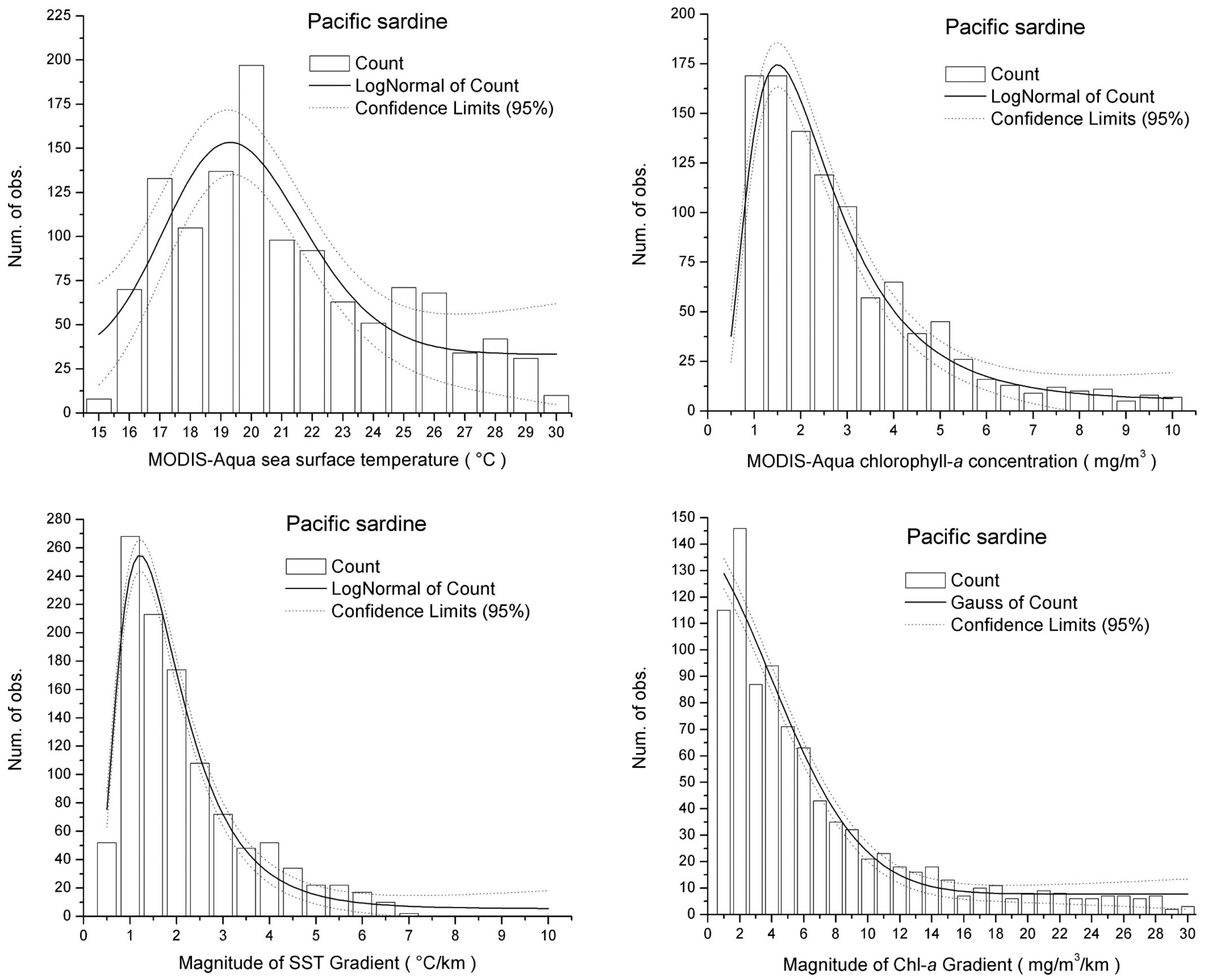

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for Pacific sardine (*Sardinops sagax)* for the period 2002–07.

(fig. 5) supports this relationship as do alternating patterns of fisheries-associated environmental parameters. This is reflected in an increase in anchovy abundance when the SST increases and the Chl decreases. Although most catches are made at the end of spring (May), fishes are abundant during the cold season, especially in spring (April–May) and early summer (June). Small pelagic fishes are present during part of the summer, decreasing in abundance towards the end of August and September, except for Pacific sardine, which become the most prominent fish. Incorporating this temporal information can provide insight on the presence/absence of certain species due to environmental features and be used in management. Although the seasonal CPUE presents a common trend over the years, there are fluctuations in the fishing season from year to year. These fluctuations were not analyzed in this study.

In the GC, the spatial distribution of oceanographic conditions varies considerably (Lavín et al. 1997; Gaxiola-Castro et al. 1999; Pegau et al. 2002). The most notable differences are at the central-upper part of the GC which has the lowest SST values and the highest Chl values (Gaxiola-Castro et al. 1999; Pegau et al. 2002). SST is much cooler at the Large Islands and the "Ballenas-Salsipuedes" channel (Isla Angel de la Guarda in fig. 2; Nevárez-Martínez et al. 2001). This suggests that cooler SSTs in the area present unfavorable conditions for Pacific sardine and basically for all species (fig. 5). The distribution of Chl in the GC is characterized by higher levels of nutrient enrichment in shallower waters close to the coastline (Gaxiola-Castro et al. 1999; Pegau et al. 2002). Previous studies have documented the productivity of these areas, where oceanographic processes such as wind stress cause nutrient enrichment of surface waters

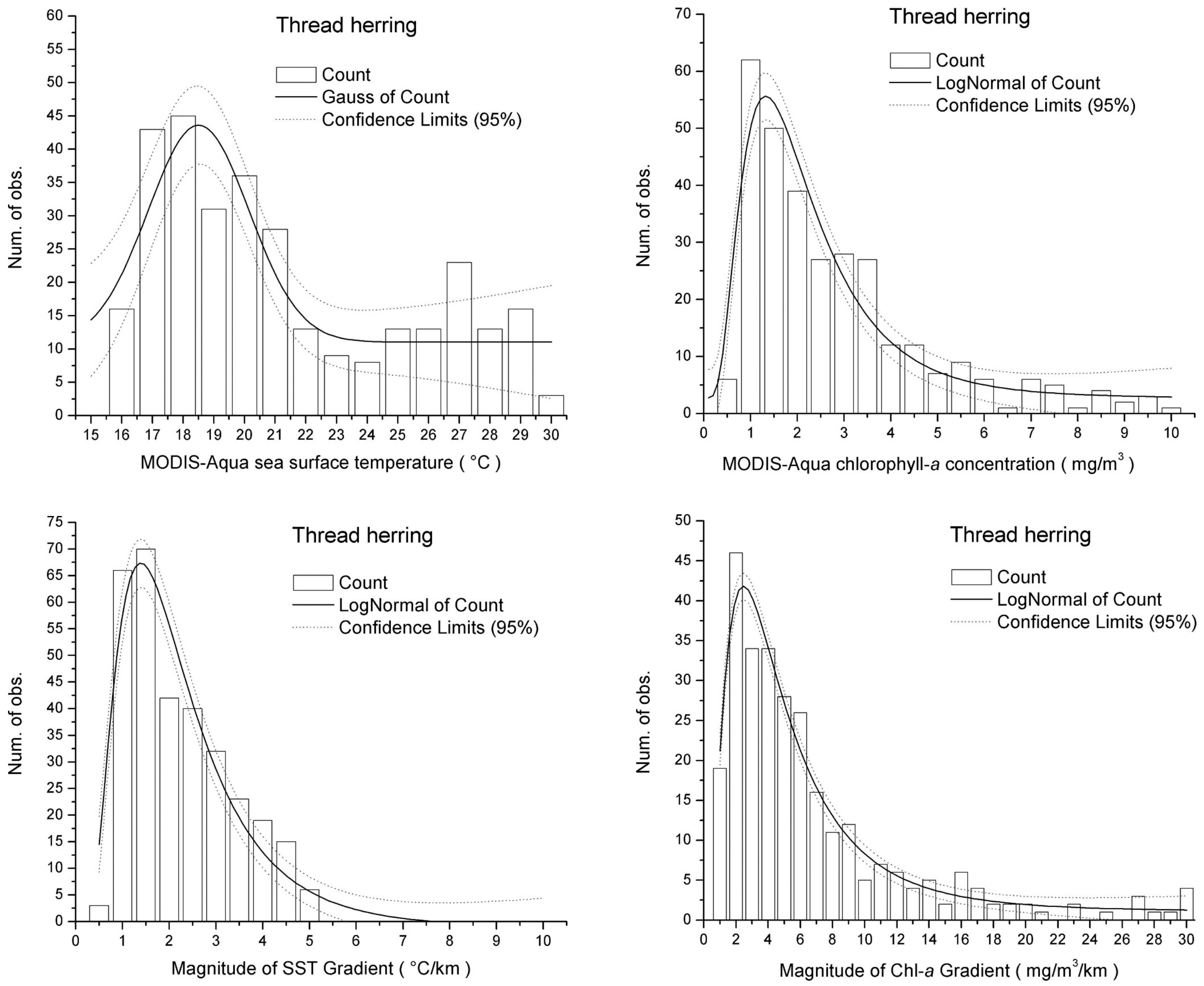

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for thread herring (*Opisthonema libertate*) for the period 2002–07.

(Santamaria-del-Angel et al. 1994; Lluch-Belda et al. 1995; Cury et al. 2000; Bakun and Broad 2003). It is likely that small pelagic fishes select these areas due to the higher concentration of food associated with these productive waters (Fréon et al. 2005, and Brown et al. 2006). On the other hand, cooler SST can be indicative of nutrient-enrichment processes, such as wind mixing, upwelling and river-run off, which are associated with favorable conditions for small pelagic fishes.

Gradient maps (GSST and GChl) derived from spatial components (horizontal and vertical differences among neighboring pixels) had a better fit with catch distribution than the single parameters of SST and Chl. The relationship between the magnitude of the SST or Chl-concentration gradient and fish presence was generally significant (tabs. 3 and 4), with a strong negative effect at steeper gradients. This was especially the case for chub mackerel presence and Chl concentration (fig. 4). The relationship between Chl concentration and fish presence was generally high with considerable uncertainty where Chl concentration was high due to a low number of values (fig 4). SST was generally the least important variable. The relationship between SST and fish presence varied considerably, especially for mackerel, which had the largest range and variation in preferences (fig. 4). However, Figure 4 and Table 1 illustrate that mackerel prefer warmer waters (25.0°–29.0°C) than do the rest of the species.

Environmental Preferences of Small Pelagic Fish

Several authors have investigated the relationship between small pelagic fishes (e.g., Pacific sardine) and SST and the upwelling index in the GC (Lluch-Cota 2000; Nevárez-Martínez et al. 2003) and found that the rela-

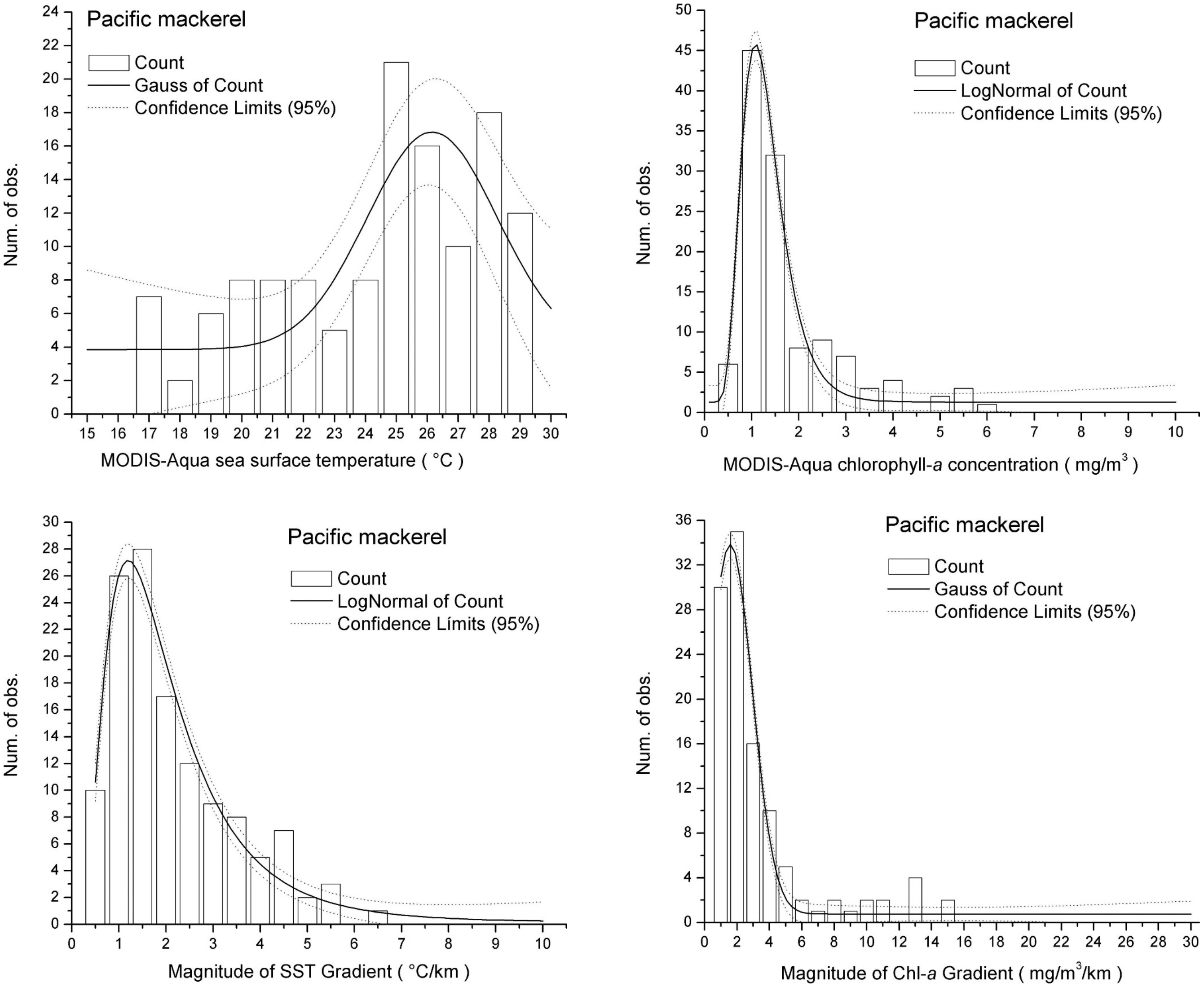

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for Pacific mackerel (*Scomber japonicus*) for the period 2002–07.

tionships between small pelagic fishes and SST were typically weaker and less significant than those between small pelagic fishes and Chl concentration. This suggests that Chl is an indicator of conditions favoring most small pelagic fishes. Chl concentration is a measure of the standing stock of phytoplankton in surface waters; therefore higher concentrations are likely to be associated with productive feeding grounds for planktivorous fish, such as small pelagic fishes. SST is likely to be less correlated with fish abundance than Chl. However, in the GC a time lag of 1–2 weeks may produce stronger relationships with fish abundance (Bakun and Broad 2003). For example, enrichment events indicated by high Chl and low SST may be more associated with the presence of certain small pelagic fish after sufficient time has passed for both zooplankton abundance to rise and fish to locate the area.

Identifying parameter preferences for small pelagic fish requires considering a variety of data issues. Among them are the highly dynamic nature of fisheries data on varying temporal and spatial scales which means that the use of satellite remote-sensing data must take into account this variability. This involves a variety of spatial ground resolution (e.g., 4 km vs 9 km), and temporal data composites (e.g., daily, weekly, monthly composites). In this study, this spatio-temporal uncertainty was not validated with in situ information. Therefore, the preferences analysis presented in this study does not accurately predict the areas where fish will be present. Instead it serves as a tool for identifying areas where environmental conditions are suitable or unsuitable for fish. Another aspect is that the environmental conditions which have been shown to influence fish distribution vary spatially and temporally and long time series of fishing data should be consid-

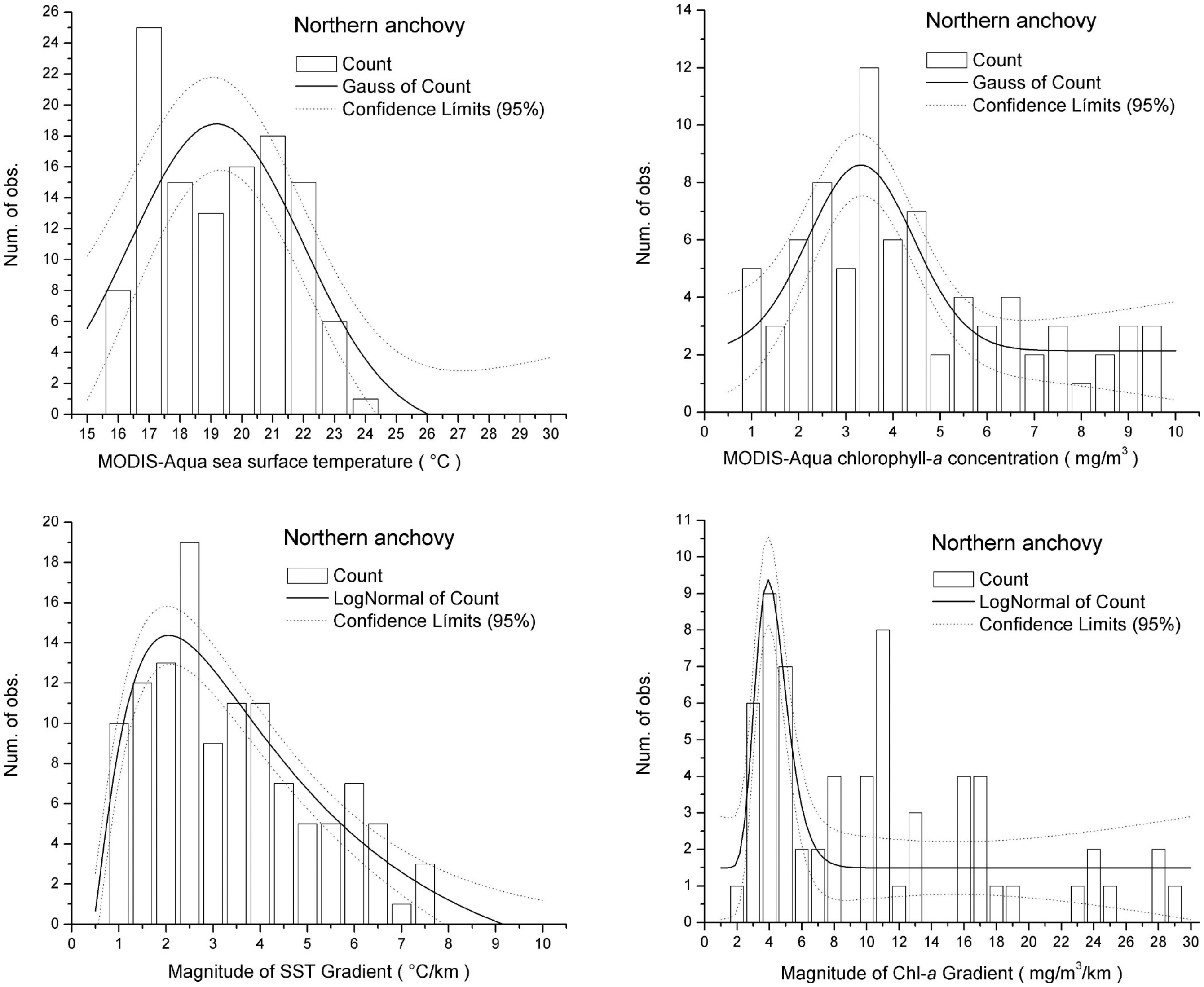

Figure 4. Frequency distribution of SST, Chl, GSST and, GChl for northern anchovy (*Engraulis mordax*) for the period 2002–07.

ered. Among this environmental variability, large interannual variations, such as El Niño/Southern Oscillation, reflect substantial temporal changes in the distribution and abundance of small pelagic fishes in the GC (Lluch Belda et al. 1995). This has considerable implications for the fishery and can alter the catchability of fish and the migration or replacement of other opportunistic or well-adapted fishes, such as mackerel (Fréon et al. 2005). Among the small pelagic fishes, the relative abundance of a single species signifies its dominance in the ecosystem and its ability to use resources. In some cases, different species may compete for the same biological niche. For example, the rise in the population of one small pelagic fish may be associated with a decline in the population of another, as for northern anchovy and South American pilchard (Christy 1997). Sardine population changes, however, are seemingly related to environmental variability (Nevárez-Martínez et al. 2003), whereas the spatial pattern of abundance for another competitor (e.g., northern anchovy) appears to be inversely related to sardine population abundance (Rodríguez-Sánchez et al. 2002; Lluch-Belda et al. 2003b). According to the literature, thread herring is relatively more frequent in the southern part of the GC—especially the ports of Guaymas and Yavaros—when Pacific sardine are scarce, such as occurred from 1990 to 1993 and during the 1997–98 fishing season; both were El Niño periods (Anonymous 2001).

The statistical approach in this study did not reflect such changes in fish distribution, which leads to another challenge. The catchability of fish is particularly important in the Gulf of California because the fishing industry is regulated by effort and gear restrictions, not quotas. Fishing is not required to cease once a certain

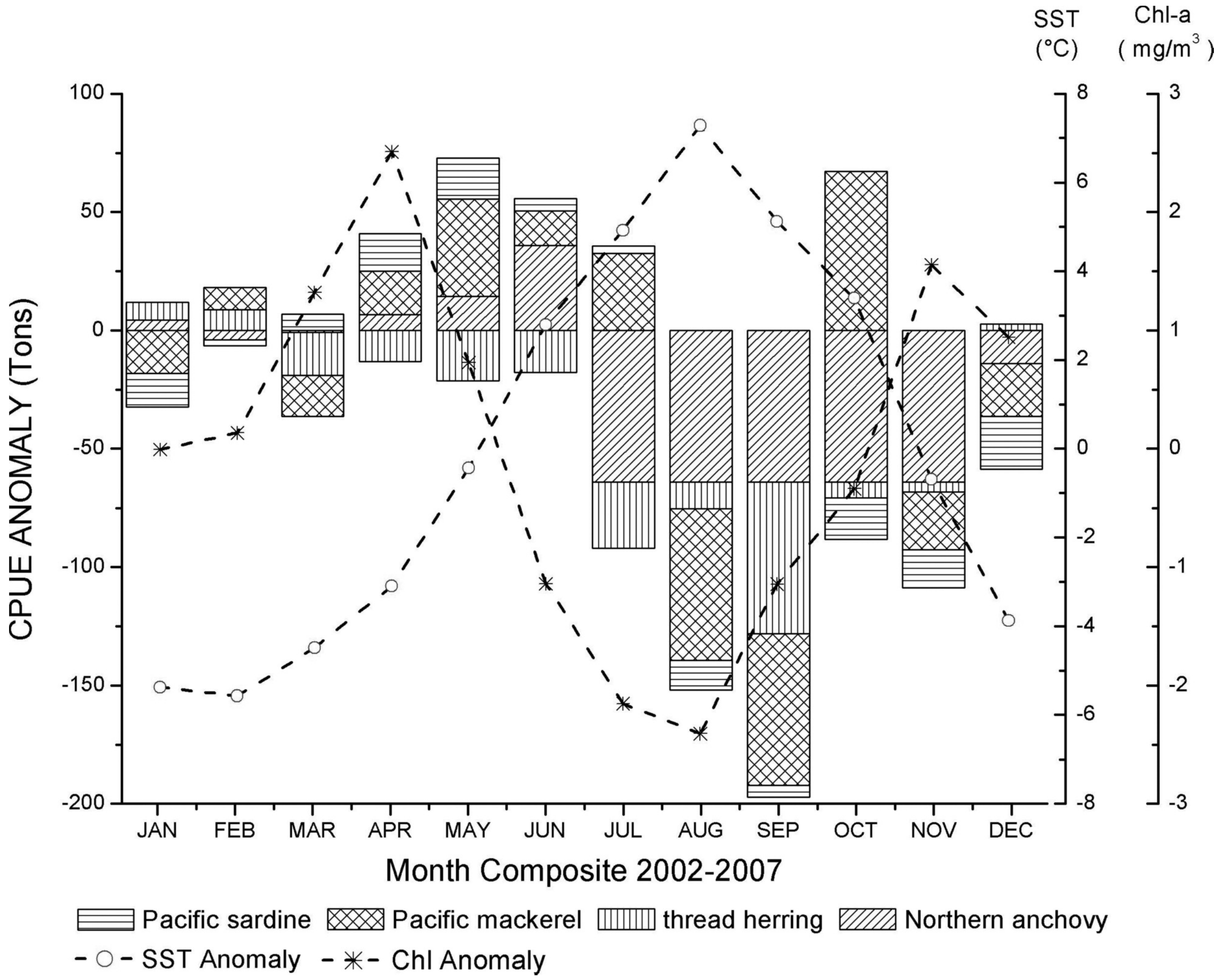

Figure 5. Normalized values of average monthly composites of catch and remote-sensed SST during 2002–07 in the Gulf of California.

amount of fish are landed. Therefore, an increase in the catchability of a stock will alter the perceived relationship between environment and fish. Increasing commercial landings may give the false impression that fish are becoming more abundant (based on number of observations or landings), when they are actually only becoming more available to fishing. Over short time scales, environmental variability can change fish distributions with considerable fishery implications (Fréon et al. 2005). For example, rapid horizontal and vertical migrations can be induced, altering the distribution of fish and therefore their availability to fishing. While many of these shifts in distribution may be relatively local and temporary, they have been observed to persist for several months and over large areas, greatly influencing the exploitation of populations (Bertrand et al. 2004).

Frequency analyses illustrated fish presence and its relationship with environmental conditions through GIS maps. In this study, these relationships were not defined as habitat with a predicted probability of presence above a specific threshold value. The relationships between the environmental factors and the small pelagic fishes are likely to result from differences in the species composition of the pelagic community. Thus, these relationships vary with species, independent of abundance, and analyses should be performed on an individual basis. Therefore, grouping all fish together is likely to obscure some relationships, particularly those of less abundant species.

CONCLUSIONS

In this study, we explored the association between small pelagic fishes with sea surface temperature and chlorophyll-*a* concentrations in the GC. For most pelagic species studied here, fish abundance was more closely related to Chl than SST distribution. Moreover, gradient maps describe more efficiently these preferences than the raw parameters. Small pelagic fishes seem to prefer oceanic waters with relatively low gradients over more productive waters (e.g., instantaneous upwelling event which produces higher primary productivity). Pacific sardine was an ideal species to describe such associations, because it is caught in a wide SST range (14.5°–31.6°C) and is found most often in waters at 17.0° to 22.0°C. Pacific sardine are found in waters with Chl concentrations ranging from 0.57 to 10.7 mg/m^3 but they prefer 1.0 to 3.0 mg/m^3. However, anchovy showed an anomalous preference for respect to SST and Chl even in the gradient maps.

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20TH CENTURY VARIABILITY IN GULF OF CALIFORNIA SST

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ABSTRACT

We estimated annually-averaged sea surface temperature (SST) anomalies for four 2° × 2° quadrants in the Gulf of California, Mexico using ICOADS (International Comprehensive Ocean-Atmosphere Data Set) and ERSST (NOAA Extended Reconstructed SST) data. We compared the anomalies to large-scale environmental indices (Pacific Decadal Oscillation index, PDO; and Nino 3 index, N3). Hamming filters were used to isolate high (<10 years), decadal (10–20 years) and low (>20 years) frequencies for comparison. The relationships between the decadal-scale variations and the relative abundance of stocks being harvested by two important fisheries (penaeid shrimps and California sardine, *Sardinops sagax*) were explored. We found that sardine relative abundance coincides well with estimated SST, increasing during the cooling intervals and declining through the warming periods, as expected given the Gulf of California is the southernmost limit of its distribution. Shrimp abundance appears to increase during warming intervals with a three-year lag which remains unexplained.

INTRODUCTION

The Gulf of California has received much attention in recent years given its unique oceanographic, ecological and fisheries characteristics. While several studies on this ecosystem have been published (Lluch-Cota et al. 2007 and references therein), the low-frequency of environmental variability at time-scales longer than a year has seldom been dealt with due to the unavailability of long-term synoptic environmental data series. Widespread concern over global climate change and its impacts on marine populations and ecosystems suggests the need for reconstruction of long-term time series of environmental data.

Although the California Current system, including the west coast of the Baja California peninsula, is one of the best known marine ecosystems—mostly due to the extensive and intensive research efforts by CalCOFI over the last century—the Gulf of California has often been regarded as a separate and mostly different ecosystem (Lluch-Belda et al. 2003a). This makes it difficult to extrapolate the already reasonably well known climate variation of the west coast to the Gulf. Furthermore, the paucity of in situ data series has prevented the completion of equivalent analyses.

Recently, more complete data series have been made available, at least of sea surface temperature (SST) variations, and notably the ICOADS (International Comprehensive Ocean-Atmosphere Data Set Release 2.0) and ERSST (NOAA Extended Reconstructed SST) data. These series provide monthly averaged SST at a 2° × 2° resolution for several quadrants in the Gulf. While the ICOADS data are actual averages of in situ data, the ERSST data are the results of interpolation. The question remains whether the result of that interpolation could be biased given the close vicinity of the open-ocean SST values along the west coast. It would therefore seem to be more convenient to approach the problem using ICOADS data, but numerous gaps in the series suggest that the interpolated ERSST data should be reconstructed in order to fill such gaps, if possible.

On the other hand, it has been suggested that the Gulf ecosystem functions as the southernmost extension of the California Current system (Lluch-Belda et al. 2003b), and that much more interchange occurs between it and the west coast of the peninsula. This was particularly suggested regarding sardine (*Sardinops sagax*) populations, which appear to move regularly between the inside of the Gulf and the peninsula west coast (Félix-Uraga et al. 2005). Furthermore, large-scale interchange during certain periods, such as that of the mid-1970s (Rodríguez-Sánchez et al. 2002), emphasizes the continuity between the west coast ecosystem and that in the Gulf. This interchange would require a certain degree of coherent variation, at least.

If such is the case, during cold periods sardines would have been distributed toward their southern limits, where low temperatures, allow abundance to increase (Lluch-Belda et al. 2003b).

On the other hand, there have been attempts to relate the abundance of other fishery resources to environmental variation in the Gulf, such as for penaeid shrimp (*Penaeus* spp.) abundance (Castro-Aguirre 1976[1];

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[1] Castro-Aguirre, J. L. 1976. Efecto de la temperatura y la precipitación pluvial sobre la producción camaronera. Paper presented at the Simposio sobre biología y dinámica de poblaciones de camarones, Instituto Nacional de Pesca, Guaymas, Sonora. Centro Interdisciplinario de Ciencias Marinas, IPN. Av IPV s/n. Col Playa Palo de Sta Rita. La Paz, BCS, 23096, Mexico. jlcastro@ipn.mx.

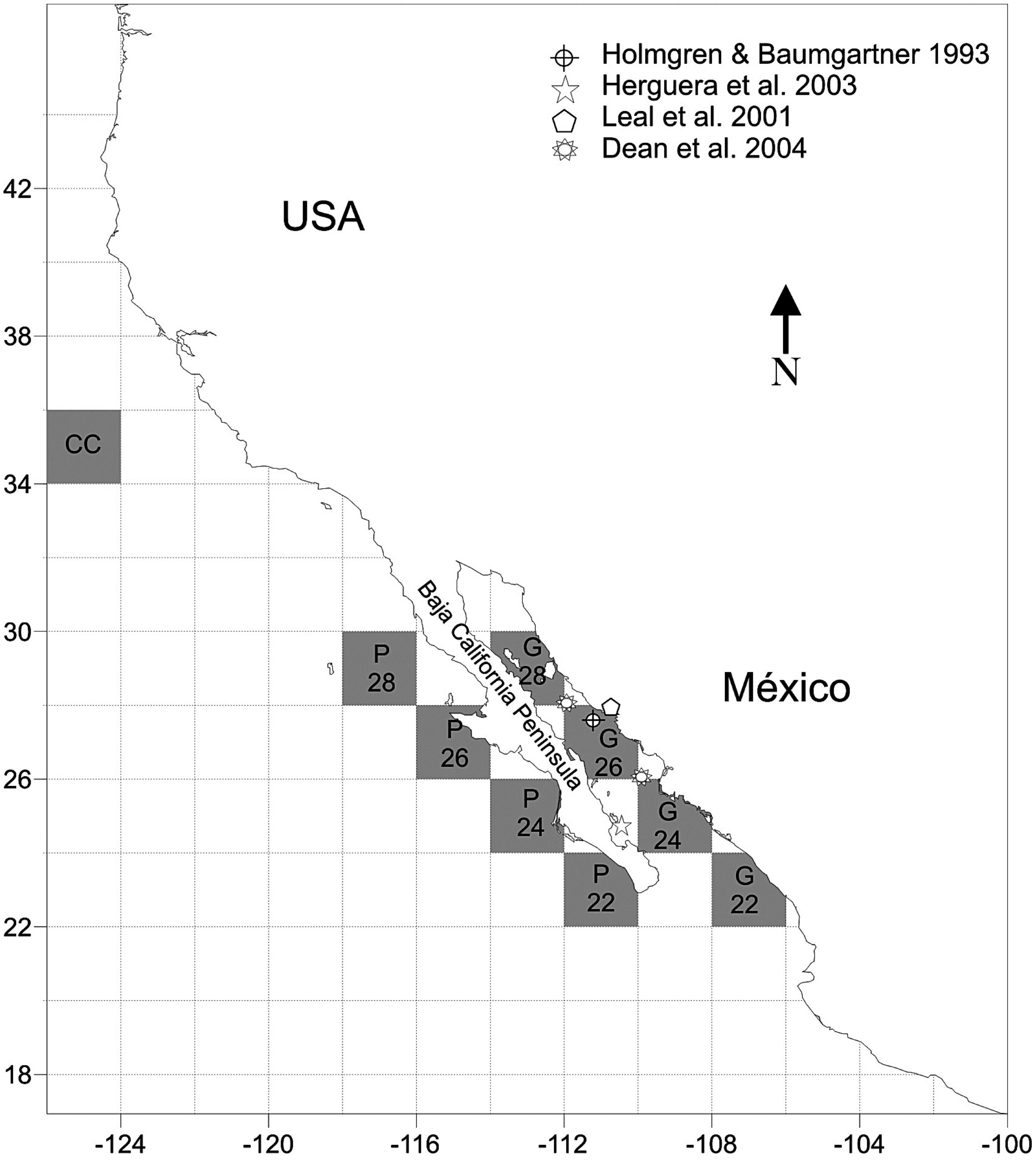

Figure 1. Areas (quadrants) for SST monthly averages, 2°x2° for the California Current (CC); coastal Pacific quadrants (PXX); Gulf of California quadrants (GXX). XX stands for the latitude of the south limit of each quadrant. Symbols refer to approximate location of sea surface temperature (SST) data, from previously published reports, as shown in the upper right box in the map and in text.

Castro-Ortiz and Lluch Belda 2007). The abundance of other fishery species, such as the giant squid (*Dosidicus gigas*), has been suspected to vary mostly due to environmental forcing (Nevárez-Martínez et al. 2000). In all cases, long-term environmental variation estimates have not been available.

In this study, we propose a reconstruction of the large-scale environmental variation in the Gulf of California, using SST anomalies at four 2° × 2° quadrants, covering most of the Gulf's surface, and compare the result to previously published series and fishery species abundance.

DATA AND METHODOLOGY

Data

For the purpose of reconstruction, data for monthly-averaged SST at four 2° × 2° quadrants, covering most of the Gulf of California (fig. 1), were downloaded from ICOADS (International Comprehensive Ocean-Atmosphere Data Set Release 2.0, available at http://icoads.noaa.gov/; downloaded on 09/07/2006; fig. 2) and for the same quadrants from the ERSST data set (NOAA Extended Reconstructed SST data, by NOAA

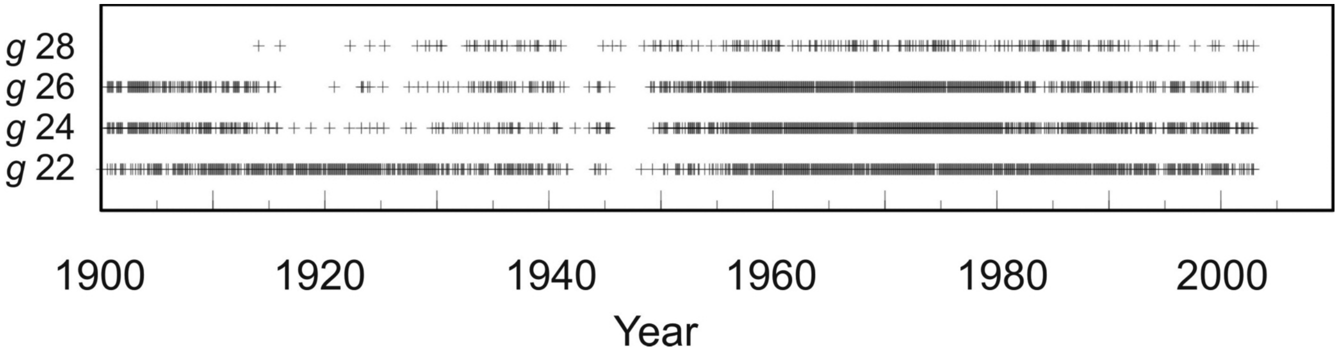

Figure 2. Temporal coverage of available ICOADS monthly sea surface temperature SST averages in the Gulf of California quadrants in Figure 1. Each cross represents one datum.

Satellite and Information Service, http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php). The 2° × 2° quadrant data were used because the coverage extends backwards well beyond the beginning of last century, while other resolutions such as 1° × 1° only go back to the mid 1900s. Figure 2 shows the temporal coverage of the ICOADS data for the quadrants chosen.

We also used annually-averaged SST anomalies for equally-sized quadrants along the western coast of the Baja California peninsula, each at the same latitude as the one inside the Gulf, plus another regarded as representative of the California Current, all previously estimated (Lluch-Belda et al. 2001, 2003a, 2005; fig. 1).

To compare them to other published series, SST data from figures in several articles were digitized: Herguera et al. 2003 presented the reconstruction of SSTs from an isotopic record preserved in the calcitic shells of the planktonic foraminifer *Globigerina bulloides* from a box core retrieved from 400 m-deep waters in the La Paz Bay Basin; Leal-Gaxiola et al. 2001 used monthly sea surface temperatures from the Guaymas tide gauge from 1979 to 1994; Lavin et al. 2003 based estimates of SST anomalies for four major areas of the Gulf (north, islands, central and south) on satellite data—eight-day averages with an approximate resolution of 18 km × 18 km, from January 1984 to December 2000; finally, Dean et al. 2004 used geochemical data (% Ti) of sediments from two box cores sampled at 0.5 cm intervals to reconstruct the PDO index. The approximate locations of each sample are shown in Figure 1, except for the Lavin et al. 2003 data, which were based on satellite data for the entire Gulf.

Large-scale environmental indices included the PDO and N3 (Pacific Decadal Oscillation Index and Nino3 index, available at http://www.cdc.noaa.gov/ClimateIndices/List/#CAR).

Sardine scale abundances in the anaerobic laminated sediments of the Gulf of California in 10 year intervals are from Holmgren-Urba and Baumgartner 1993 (location also shown in fig. 1); sardine landings data were provided by R. Félix Uraga[2]. Shrimp landings from off the Pacific coast of Mexico were taken from the work of Lluch-Belda 1977 and Magallón-Barajas 1987. Data were also obtained by digitizing figures from the management plan for the fishery (available at www.sagarpa.gob.mx/conapesca/ordenamiento/PLAN_DE_MANEJO_CAMARON_OP_agosto_.pdf) and the national fisheries chart (www.sagarpa.gob.mx/conapesca/ordenamiento/carta_nacional_pesquera/cnp.htm). It should be stressed that shrimp landings in the Gulf of California are the major component (about 80%) of the total Pacific coast landings; although it would be desirable to have the data from the Gulf, they are not available for the full time used in this study.

Methodology

To reconstruct the Gulf ICOADS environmental data series we first estimated climatologies for the ERSST (identified by *e* and the southern latitude of the quadrant, from now on) and ICOADS (*c* from now on, similarly) series for the Gulf quadrants and monthly anomalies were estimated as departures from the climatology. This procedure permits eliminating variation from the annual cycle, which is the strongest signal. Simple linear correlation was then estimated for the anomaly series (tab. 1).

Next, the relationship between the ERSST and ICOADS series was estimated with simple linear regression (*e* as independent, *c* as dependent variables, tab. 2). Then the gaps in the *c* series were filled by reconstruction using these relationships. Later, annual anomalies were estimated as the mean of the monthly anomalies for each of the resulting series, labeled *g* from now on.

These *g* series were correlated to large-scale environmental variables (PDO for the north Pacific variation and N3 for the tropical condition) by means of multi-

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TABLE 1

Correlations between the ERSST and ICOADS monthly anomaly series for quadrants in the Gulf of California. Above and right, number of pairs; left and down, correlation coefficients. Bold numbers indicate statistical significance at $p > 0.05$

	*e*22	*e*24	*e*26	*E*28	*c*22	*c*24	*c*26	*c*28
*e*22		1236	1236	1236	894	680	666	220
*e*24	**0.93**		1236	1236	894	680	666	220
*e*26	**0.88**	**0.98**		1236	894	680	666	220
*e*28	**0.56**	**0.69**	**0.80**		894	680	666	220
*c*22	**0.48**	**0.30**	**0.25**	**0.12**		568	536	184
*c*24	**0.56**	**0.64**	**0.61**	**0.36**	**0.27**		556	163
*c*26	**0.40**	**0.47**	**0.47**	**0.36**	**0.14**	**0.53**		164
*c*28	**0.17**	**0.29**	**0.33**	**0.30**	–0.07	**0.25**	**0.26**	

TABLE 2

Linear relation equations between the ERSST and the ICOADS series. Numbers following letter indicate North latitude of the southern limit of the quadrant. *c*XX, ICOADS data; *e*XX, ERSST data

$c22 = 1.3352 + 0.94820\ e22;\ r = 0.91$

$c24 = 1.7622 + 0.93463\ e24;\ r = 0.94$

$c26 = 2.1345 + 0.92818\ e26;\ r = 0.91$

$c28 = 6.9996 + 0.61269\ e28;\ r = 0.70$

ple regression of *g* on PDO and N3. Later, the *g* series were correlated to those from Herguera et al. 2003, Lavin et al. 2003 and Leal-Gaxiola et al. 2001.

The first principal component (PC1) of the Pacific (PPC1) and the Gulf (GPC1) series were extracted. Then Hamming filters were used to isolate high (<10 years), decadal (10–20 years) and low (>20 years) frequencies to compare with formerly identified trends (Lluch-Belda et al. 2003a). The Dean et al. 2004 series was then cross-correlated to the GPC1 and the filtered frequencies.

Shrimp landings data are for all of the Pacific coast and from different sources. We used the head-off landings reported in Lluch-Belda 1977; Magallón-Barajas 1987, while from Plan de Manejo and Carta Nacional Pesquera data we used live weight; since the series overlap, the first two were scaled to heads on by multiplying by a factor obtained from their averaged difference along the overlapping years. Then, they were averaged for the common years.

RESULTS

The ICOADS series contains a reasonable amount of directly observed data, although there are numerous gaps particularly northward. Certain periods are mostly devoid of information, such as the 1940s (fig. 2). The significant correlations between the ICOADS and the ERSST anomalies (tab. 1) allow the ICOADS series to be reconstructed using the linear relationship between the two (tab. 2). The relationships show that there is some degree of smoothing in the ERSST series, as seen by slope values that are compensated by positive intercepts; the amount of smoothing increases from south to north.

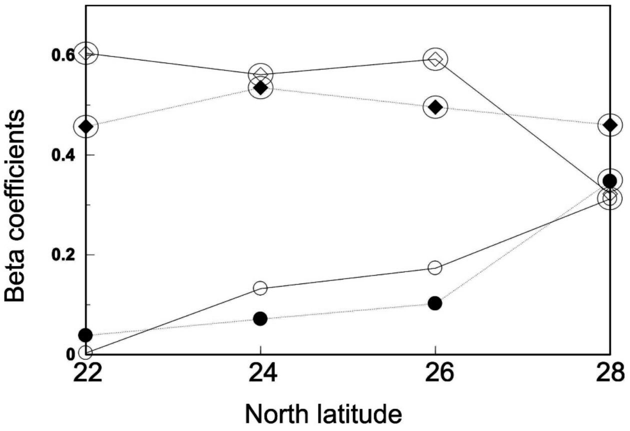

Figure 3. Multiple correlation regression coefficients of sea surface temperature anomalies on the Pacific Decadal Oscillation Index (PDO$^{\bigcirc}$) and NINO3 index (N3$^{\diamond}$) for the Gulf of California (*g*, filled symbols) and coastal Pacific (*p*, hollow symbols).

TABLE 3

Correlation coefficients between the *g* series and the Herguera et al. 2003 series. Bold numbers indicate statistical significance at $p > 0.05$

	Herg An	*g*22	*g*24	*g*26	*g*28
Herg An		0.23	**0.58**	**0.57**	**0.46**
*g*22	0.23		**0.62**	**0.43**	**0.41**
*g*24	**0.58**	**0.62**		**0.77**	**0.54**
*g*26	**0.57**	**0.43**	**0.77**		**0.60**
*g*28	**0.46**	**0.41**	**0.54**	**0.60**	

TABLE 4

Linear correlations between the monthly averages of the Lavin et al. 2003 series and the Gulf of California ones. Bold numbers indicate statistical significance at $p > 0.05$

	Lavin	*g*22	*g*24	*g*26	*g*28
Lavin		**0.27**	**0.49**	**0.42**	**0.36**
*g*22	**0.27**		**0.38**	**0.16**	0.09
*g*24	**0.49**	**0.38**		**0.37**	**0.27**
*g*26	**0.42**	**0.16**	**0.37**		**0.34**
*g*28	**0.36**	0.09	**0.27**	**0.34**	

The correlations between latitudinal quadrant anomalies and large-scale environmental indices (PDO and N3) for the coastal Pacific and Gulf series show similar trends (fig. 3). This may mean that the global environment is mostly forced by the atmosphere, rather than by the ocean through the Gulf mouth.

The reconstructed *g* series correlates well with those of Herguera et al. 2003 (tab. 3), which is a long series in a specific location (the La Paz Bay), and Lavin et al. 2003 (tab. 4), which is a short series of the full Gulf, but not with the Leal-Gaxiola et al. 2001 series (tab. 5), which is a short series in a very specific spot (the Guaymas Bay).

Filtered series from the Gulf and the Pacific PC1

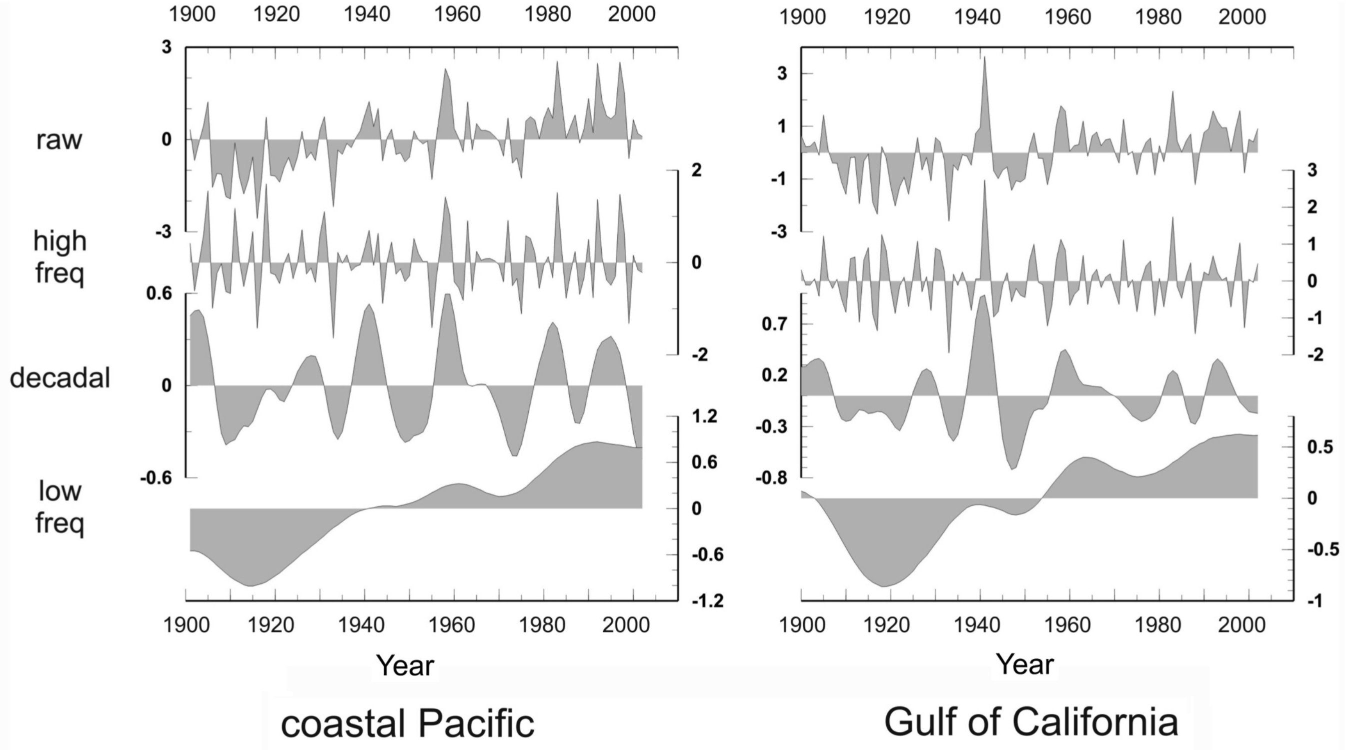

Figure 4. Raw and Hamming filtered series for the coastal Pacific (left) and Gulf of California (right) first principal component (PC1) of the sea surface temperature anomalies series.

TABLE 5

Linear correlations between the monthly anomalies at the Guaymas tide gauge (Leal et al. 2001) and the *g* series, 1979 to 1994. Bold numbers correspond to statistical significance at $p > 0.05$

	Leal	*g*22	*g*24	*g*26	*g*28
Leal		–0.12	–0.13	0.02	–0.10
*g*22	–0.12		**0.41**	**0.18**	0.03
*g*24	–0.13	**0.41**		**0.49**	**0.23**
*g*26	0.02	**0.18**	**0.49**		**0.26**
*g*28	–0.10	0.03	**0.23**	**0.26**	

(fig. 4) display mostly similar trends, although some differences are also evident; perhaps the most striking being the positive peaks of the early 1940s (stronger for the Gulf series), and the early 1960s (stronger in the Pacific series).

The Dean et al. 2004 series cross-correlates with the raw GPC1 (0.4589 with a delay of 2 years, GPC1 leading) and with the long-term trend (Hamming filtered by 30 years), also with a delay of 2 years, GPC1 leading (0.6189), both significant.

Sardine relative abundances (estimated from scales in anoxic laminated sediments and landings) are shown in Figure 5 with the Gulf decadal-filtered PC1 series, and periods of cooling and warming. The cooling period of 1940–53 corresponds well with sardine abundance increase, while the following decline corresponds with the warming period through 1960. There is also a smaller increase in abundance afterwards, coincident with the cooling period after 1960.

The landings peak during 1990 corresponds with a cooling period extending from 1987 to 1990, although it could also be confused with the increase in effort by the fishery. While the decline in abundance during the early 1990s has been blamed on overfishing, it occurred during a warming lapse, which may indicate another reason for the decline. Finally, the following dip was likely related to the impact of the 1997–98 El Niño preventing the expansion of sardine schools southward to the usual fishing areas, as proposed for previous events (Lluch-Belda et al. 1986). This was a temporary effect occurring during a cooling lapse that permitted the fishery to rebound immediately afterwards.

The shrimp landings series are shown in Figure 6, together with the 10-years smoothed GPC1. Landings are cross-correlated to the raw GPC1 with a lag of three years (0.4075, $p < 0.05$, GPC1 leading), but not to the high or decadal frequencies.

DISCUSSION

The reconstruction of the large-scale SST anomalies at the four gulf quadrants appears robust because it agrees with other records, particularly those showing major climate signals; it also avoids the smoothing effect of the

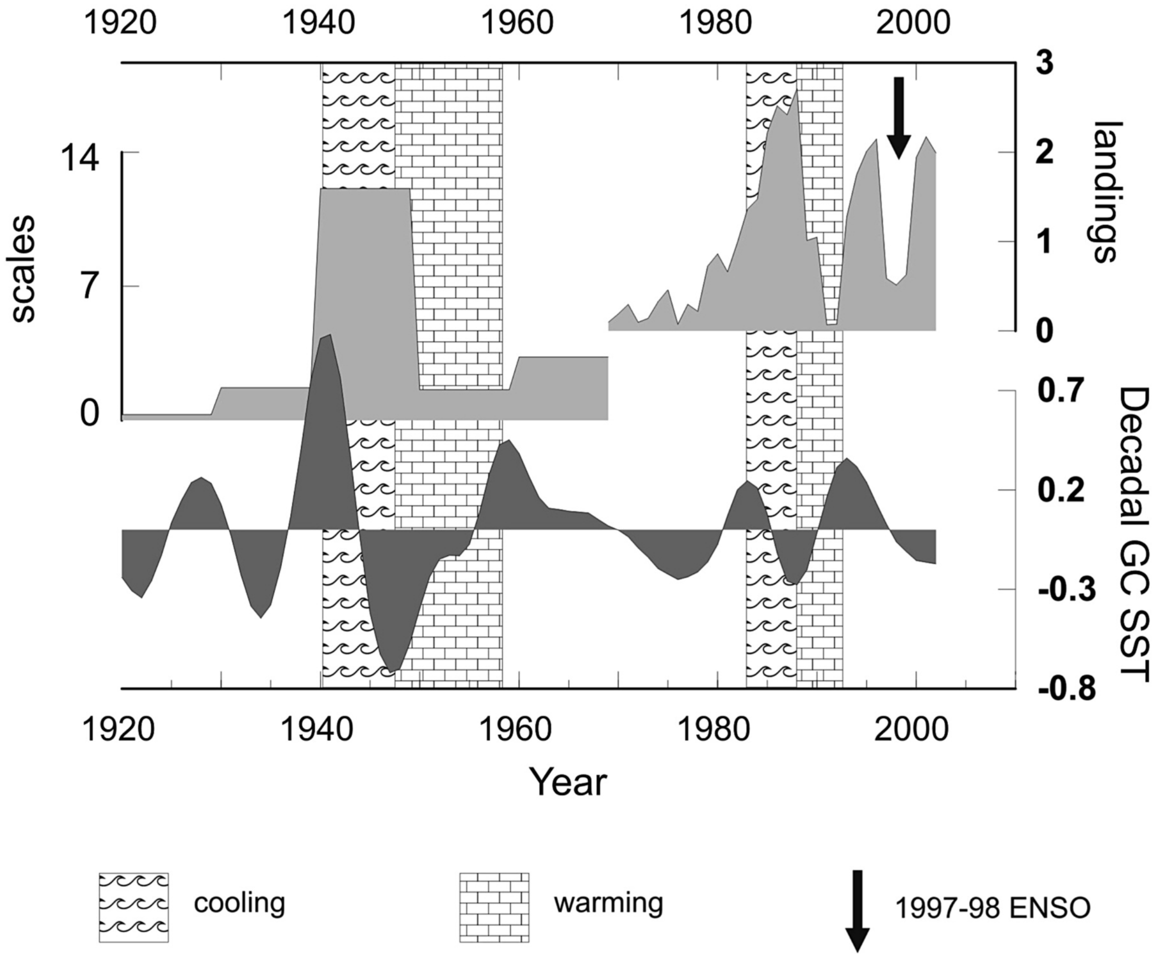

Figure 5. Comparison between the decadal filtered of the first principal component of the sea surface temperature anomalies at the Gulf of California and sardine relative abundance indices: scales in anoxic varved sediments and landings.

ERSST interpolation process. Published large-scale series vary similarly to the reconstructed data, as do proxies derived from sediment deposition data. No correlation was found with the data from Leal-Gaxiola et al. 2001, which corresponds to SST data at a very specific spot and thus largely depends on local conditions. The similarity of the relationships between the coastal Pacific and Gulf latitudinal quadrants and the large-scale environmental indices (PDO and N3) suggests that a great part of the latitudinal variability is being forced by the atmosphere, which may be because oceanic isolation between the two areas increases from south to north.

Interannual, decadal, and longer frequency trends are similar at both coasts, although some differences exist. The most relevant appears to be the relative importance of the early 1940s peak event, which is much more pronounced in the Gulf. That year has also been described as a regime shift in the North Pacific Ocean (Lluch-Belda et al. 2003a).

We found that the relative abundance of sardines covaries with the cooling and warming states of the environment which agrees with previous findings (Lluch-Belda et al. 2003b). Since the sardine population in the Gulf is at the southernmost limit of its distribution, its relative abundance is expected to be higher during cooling periods and vice versa, as was observed (fig. 5). The period of high abundance—denoted by the number of scales in anoxic varved sediments—also coincides with the cooling period right after the early 1940s, while the decline in abundance coincides with the warming lapse between the late 1940s and the early 1960s. However, sardine scales were reported in 10-year blocks (Holmgren-Urba and Baumgartner 1993) and a more reliable indicator of correlation is the coincidence of population growth from 1981 to 1988 and from 1992 to 1996, while it declined during 1989 to 1992. Further declines coincided with the strong 1997–98 ENSO, similar to what occurred during previous events (Lluch-Belda et al. 1986).

Since at least the mid 1950s, several authors have suggested a relationship between tropical shrimp abundance and rainfall (Chapa 1966; Chapa and Soto López 1969; Castro-Aguirre 1976[1]; Sepúlveda-Medina 1991; etc.).

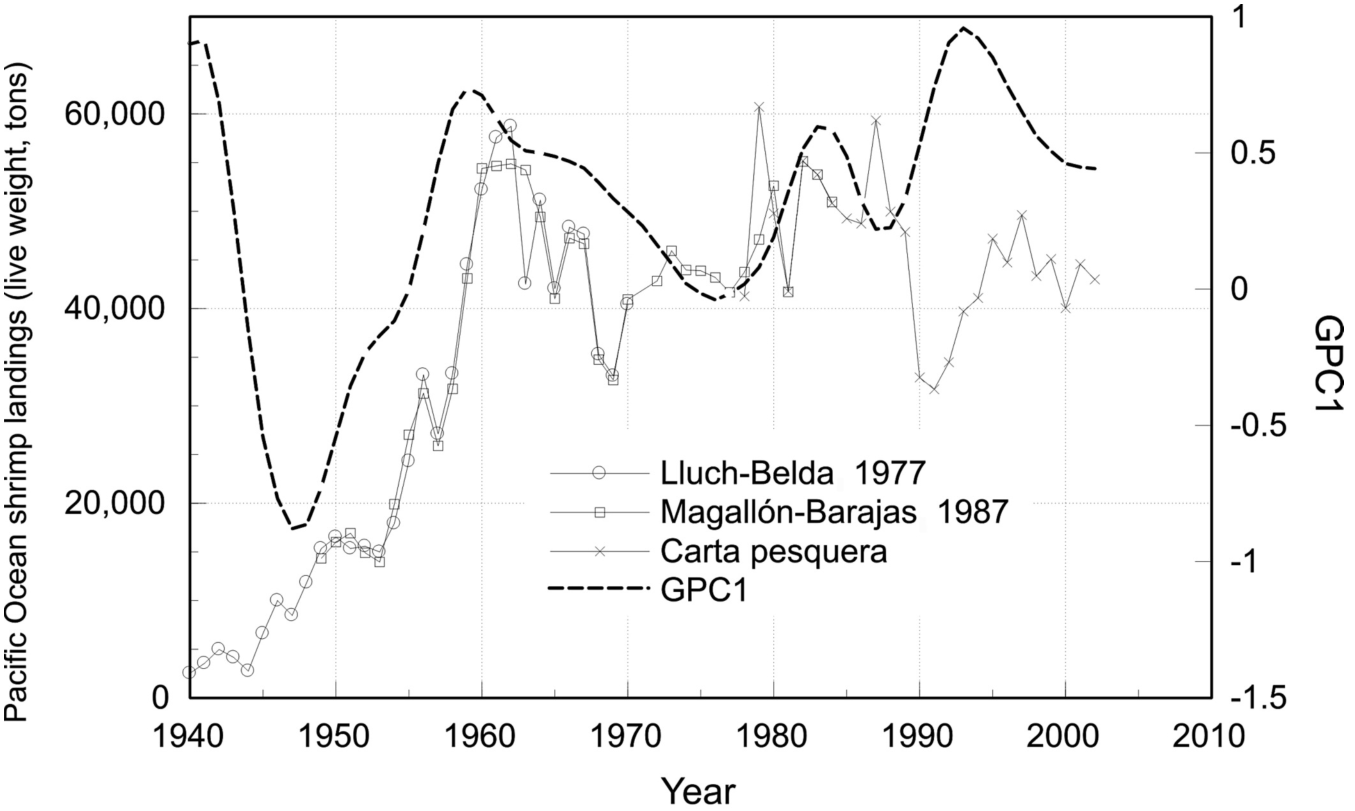

Figure 6. Comparison between the decadal filtered first principal component of the sea surface temperature anomalies (GPC1) at the Gulf of California, shrimp relative abundance indices and number of boats in the fishery. Inset denotes the reference for each shrimp abundance series. The Lluch-Belda 1977 and Magallón-Barajas 1987 series were transformed to live weight.

Both Castro-Aguirre and Sepúlveda-Medina noted a lag of two-three years between rain and shrimp abundance.

The data presented here (fig. 6) indicate a correlation between landings and the 10-year smoothed SST, although there is a clear lag. Increasing trends were similar during ~1950 to ~1960, ~1975 to ~1985 and ~1991 to ~1997; and were significantly correlated with a lag of three years, with SST leading. A major discrepancy in the relationship is the increasing landings trend between ~1970 to ~1975, when SSTs were decreasing; however, the fleet grew explosively from 762 to 1192 (56%) during those years.

Most of the reported correlation, however, is in the ~1950 to ~1960 trends; there is no significant correlation if only years after 1955 are considered. Catch per unit of effort (CPUE), estimated from yearly landings per boat, are poor estimators. There is no available information to estimate catch per standard fishing days, as done in the past (Lluch-Belda 1977).

There is also a coincidence in the lag between SST and shrimp abundance and between SST and Ti% in the Dean et al. 2004 series; Ti concentration is an indicator of increased rainfall. Why rainfall should be higher three years before the maximum SST is not yet understood.

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BALEEN WHALE DISTRIBUTION RELATIVE TO SURFACE TEMPERATURE AND ZOOPLANKTON ABUNDANCE OFF SOUTHERN CALIFORNIA, 2004–2008

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ABSTRACT

We investigated the spatial and temporal variation in distributions of three large baleen whale species off southern California in relation to sea surface temperature (SST) and zooplankton displacement volume using Geographic Information System (GIS) software. Data were collected on sixteen California Cooperative Oceanic Fisheries Investigations (CalCOFI) quarterly cruises (lines 77–93) from July 2004–March 2008. The most frequently sighted large whales were humpback whales (*Megaptera novaeangliae*, 67 sightings), fin whales (*Balaenoptera physalus*, 52 sightings), and blue whales (*Balaenoptera musculus*, 36 sightings). Blue and humpback whale sightings peaked in summer (July/August) and fin whales were most frequently seen in summer and fall, consistent with known migratory patterns. In spring through fall, whale sighting locations were associated with colder SST and greater zooplankton abundance levels compared to averages from random locations on the trackline. These results support the hypothesis that foraging distributions of large whales are linked to cold surface temperatures, which may indicate processes that enhance prey production and accumulation, such as upwelling or advection of productive water within the California Current. However, winter distributions of whales presumed to be migrating do not appear to be related to the habitat variables we analyzed, and may be harder to predict based on oceanographic data. The frequency of CalCOFI cruises provides us with high temporal resolution and an ongoing, long time series compared to other survey efforts, allowing comparison between seasons and years that will increase our understanding of these top predators and their response to habitat variability within an important subregion of the California Current Ecosystem.

INTRODUCTION

Baleen whales are highly mobile apex predators that feed on spatially patchy, ephemeral aggregations of zooplankton. Several baleen whale species seasonally forage and migrate within the productive and dynamic California Current Ecosystem (CCE), which varies markedly on seasonal, interannual and multi-year timescales (Hickey 1979; Hayward and Venrick 1998; Mullin et al. 2000; Brinton and Townsend 2003; Chhak and Di Lorenzo 2007; Keister and Strub 2008). California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises, conducted offshore of southern California every three months, provide an excellent platform to observe temporal variation in whale distribution in relation to zooplankton abundance and other habitat variables. The data provided by these frequent surveys and extensive oceanographic measurements may aid in developing predictive models of whale occurrence as a useful management and conservation tool in southern California, a region heavily used by humans for military, industrial, and other activities.

Cetacean surveys have been conducted on each CalCOFI cruise since July 2004 using both visual and acoustic detection methods (Soldevilla *et al.* 2006; Douglas et al. in prep.[1]). The most frequently sighted baleen whales during these and other surveys off southern California are blue (*Balaenoptera musculus*), fin (*B. physalus*), and humpback (*Megaptera novaeangliae*) whales, all within the family Balaenopteridae (rorquals) (Smith et al. 1986; Soldevilla et al. 2006; Barlow and Forney 2007). Blue whales off California feed exclusively on euphausiids (krill) (Fiedler et al. 1998a), whereas the diets of fin whales and humpback whales include krill as well as copepods, cephalopods, and small schooling fish such as sardines, herring and anchovies (Clapham et al. 1997; Fiedler et al. 1998a; Flinn et al. 2002).

Baleen whales in the eastern North Pacific Ocean forage primarily in summer and typically migrate to lower-latitude breeding and calving grounds in winter, although wintering grounds and movement patterns are not well known for all proportions of each population (Forney and Barlow 1998; Mate et al. 1999; Etnoyer et al. 2006). Whaling records from the early 20th century and recent surveys over the past twenty years indicate that blue and fin whales are most abundant off the coast of California in summer and fall (but seen occasionally in winter), whereas humpbacks are near the coast in sum-

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[1] Douglas, A. et al. *In prep*. Seasonality, diversity and density of marine mammal species present off Southern California, based on sighting data collected on quarterly California Cooperative Oceanic Fisheries Investigations cruises 2004–2008.

mer but further offshore in winter (Clapham et al. 1997; Forney and Barlow 1998). However, recent cetacean survey effort off California has been seasonally biased, conducted primarily from ships in summer through fall (Barlow and Forney 2007), except for two winter aerial surveys conducted in 1991 and 1992 (Forney and Barlow 1998). Continuous, year-round acoustic monitoring off southern California corroborates that blue whales are present in summer and fall and are rare or absent at other times of year (Burtenshaw et al. 2004; Oleson et al. 2007), whereas fin whale calls are detected year-round with the greatest abundance in summer through fall (Oleson 2005).

The foraging distributions of baleen whales off California vary depending on where and when their prey are concentrated, which is largely determined by marine ecosystem features and dynamic climactic and oceanic processes. Circulation within the Southern California Bight is characterized by the cold, equatorward-flowing California Current (CC) centered about 200–300 km offshore, and the strengthening in summer to fall of the Southern California Eddy and Southern California Countercurrent, which brings warm water northward along the coast (Lynn and Simpson 1987; Hickey 1992). In the CCE, wind-driven coastal upwelling in spring promotes high primary productivity (as indicated by chlorophyll concentration) followed by a subsequent increase in zooplankton production that reaches a peak in adult biomass after a time lag of one to four months (Hayward and Venrick 1998). This time lag corresponds to the interval between peak surface chlorophyll concentration and peak whale abundance off California (Burtenshaw et al. 2004; Croll et al. 2005). As upwelled, productive waters are advected southward by the CC, dense euphausiid patches may develop in areas where bottom topography and/or other features (such as eddies and fronts) contribute to retention, such as in Monterey Bay (Croll et al. 2005), and around the Channel Islands (Fiedler et al. 1998a). Keiper et al. (2005) recorded greater marine mammal sighting rates during periods of upwelling relaxation that led to stronger stratification in early to late-spring surveys, and hypothesized that these conditions contribute to stabilization and aggregation of prey.

Climatic oscillations on annual and multiyear timescales contribute to variability in production within the CCE and hence distribution of whales. For example, cetacean surveys in Monterey Bay during the late 1990s documented decreased balaenopterid whale abundance during the 1997 onset of El Niño, when krill acoustic backscatter was low, and then a sharp increase in whales as krill abundance slowly increased in 1998 (Benson et al. 2002). The authors hypothesized that the sharp increase in whale numbers within the bay was due to whales concentrating in inshore productive areas while offshore krill abundance remained low through the El Niño event. Over the past couple of decades, large-scale population assessment surveys conducted by the U.S. National Marine Fisheries Service (NMFS) provide evidence for blue whales shifting foraging grounds outside of the California-Oregon-Washington study area (Barlow and Forney 2007; Barlow et al. 2008a[2]). This shift in blue whale distribution may be associated with the overall declining trend in zooplankton displacement volumes off California since the 1990s (Goericke et al. 2007; McClatchie et al. 2008). However, NMFS surveys are conducted every three to five years primarily in summer and fall, and as such do not capture seasonal variability between years.

The CalCOFI program has conducted four cruises per year since 1949 that presently measure over 20 meteorological, oceanographic and biological variables. Since 2004, CalCOFI cruises have included systematic marine mammal visual and acoustic surveys, providing an opportunity to investigate the relationship of top marine predators to these numerous habitat variables. Previous studies in the CCE have found that baleen whale distributions are related to season and environmental variables including bathymetry, sea surface temperature, salinity, location of fronts, chlorophyll concentration, and acoustic backscatter (Smith et al. 1986; Burtenshaw et al. 2004; Keiper et al. 2005; Tynan et al. 2005; Etnoyer et al. 2006). However, habitat models are often limited by small sample sizes due to infrequent surveys/low numbers of sightings, lack of data during winter months when surveys are not typically conducted, and/or by availability of oceanographic data. For example, many studies incorporate bathymetry and remotely-sensed ocean-surface data from satellites because these data are widely available, but assumptions are required to explain physical and biological mechanisms by which surface production is transferred to macrozooplankton in dense aggregations needed to support apex predators.

This paper provides a preliminary, descriptive overview of spatiotemporal patterns in selected habitat variables and cetacean distributions within the Southern California Bight. We examined two habitat variables measured in situ during CalCOFI cruises, sea surface temperature (SST) and zooplankton displacement volume, in relation to concurrent whale sightings data. We selected sea surface temperature due to its potential to indicate physical mechanisms that lead to either production (e.g. upwelling or advection of cold, nutrient-rich water) or

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[2] Barlow J., J. Calambokidis, and K. A. Forney. 2008a. Changes in blue whale and other cetacean distributions in the California Current Ecosystem: 1991–2008. *In* California Cooperative Oceanic Fisheries Investigations annual conference 2008: Troublesome Trends or Meandering Variability?, J. Heine, ed. San Diego, CA.

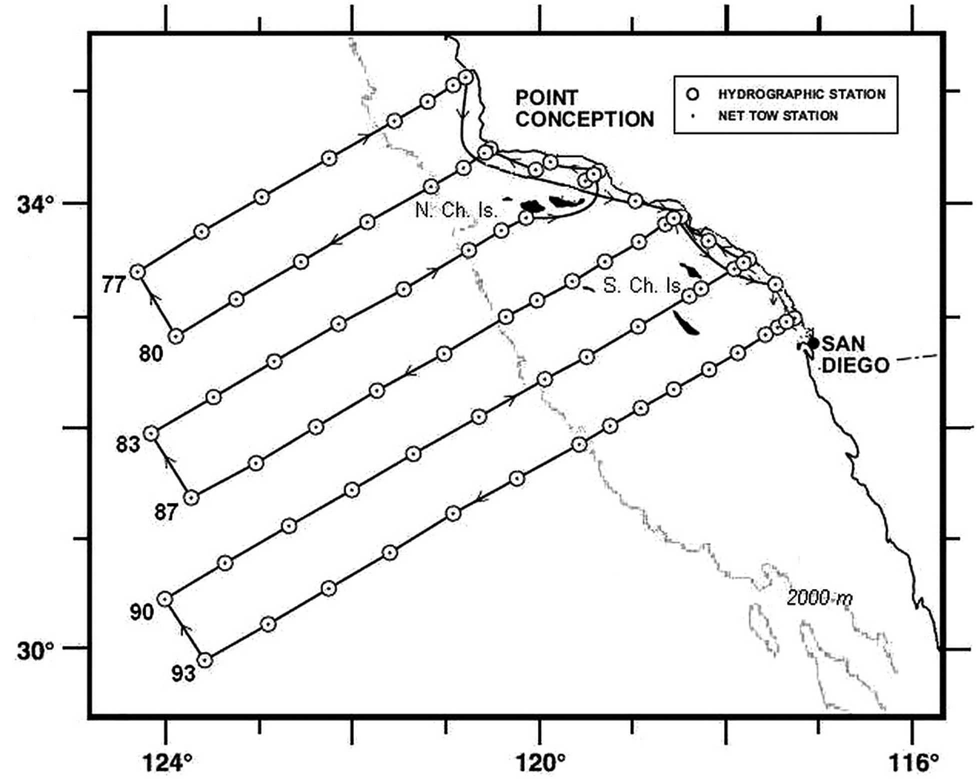

Figure 1. CalCOFI study area showing numbered ship tracklines, hydrographic and net tow stations, and northern and southern Channel Islands. 2000 m depth contour shown in grey. Figure altered from McClatchie et al. (2005).

concentration of prey (e.g. along temperature fronts or eddies). Total macrozooplankton displacement volume (a proxy for macrozooplankton abundance), is not a direct measure of krill abundance but is the best currently available dataset to represent foraging conditions for higher trophic levels. Identifying potential patterns and linkages between whale distributions, prey, and oceanographic variables will allow the formulation of hypotheses that can be tested using more rigorous statistical methods.

MATERIALS AND METHODS

Data collection

Data were collected during CalCOFI cruises off southern California (Figure 1) from July 2004 through March 2008 using Scripps Institution of Oceanography RVs *New Horizon* (NH), *Roger Revelle* (RR) and the National Oceanic and Atmospheric Administration (NOAA) RV *David Starr Jordan* (JD). Two trained marine mammal observers were posted on the bridge wings (NH, 8.1 m above water), flying bridge (JD, 11 m), or 03 level (RR, 13.2 m) and equipped with 7×50 power binoculars to locate and identify cetaceans as the ship transited between stations at 10 knots. Ship time constraints did not allow deviation from the trackline to approach unidentified cetaceans; however, "big eye" binoculars (25×50 power) were used in November 2004 and all cruises since July 2005 (JD and RR had constant access, NH had restricted access) to aid in species identification at long distances (Soldevilla et al. 2006). Mammal observers recorded sighting information including species, group size (estimated by consensus), behavior, weather and sea state; the latter two variables were also recorded periodically independent of sightings. Survey effort was curtailed in sea state Beaufort 6 or greater, or when visibility was reduced to less than 1 km. Mammal observers recorded opportunistic sightings during poor conditions and/or while on station, but these were not used in this analysis.

Sea surface temperature (SST) and other ocean-surface data were collected at approximately 2 m depth using the ship hull-mounted system and Seabird Electronics SBE-21 thermosalinograph or similar. Underway data were collected at 30-second intervals and processed with 10-minute time resolution. Underway data were not available as of this study from winter 2007 (CC0701JD) and winter and spring 2008 (CC0801JD and CC0803JD); for these cruises we analyzed on-station temperature data from CTD sensors and bottles.

Zooplankton were sampled at CalCOFI stations with a standard oblique plankton tow to 210 m (bottom depth permitting) using Bongo paired 505 µm mesh nets with

71 cm diameter openings. Total zooplankton volumes (ml) were standardized to water volume (per 1000 cubic meter strained volume). For this analysis, we removed high outlier zooplankton displacement volumes likely due to overabundance of gelatinous species (A. Hays pers. commun.[3]).

Data analysis

We used Geographic Information Systems (GIS) software to analyze whale sightings in relationship to oceanographic data. Zooplankton displacement volumes, SST, and sightings of blue, fin, humpback, and unidentified balaenopterid whales were uploaded into ArcGIS 9.2 and analyzed using Geostatistical Analyst. Zooplankton volume and SST coverages were created using two interpolation methodologies. A universal Kriging analysis was applied to the 10-minute averaged underway SST data, accounting for a northwest directional second-degree polynomial trend in temperature (Royle et al. 1981; Oliver and Webster 1990; ESRI 2008). An Inverse Distance Weighted (IDW) analysis (Watson and Philip 1985; ESRI 2008) was applied to data collected at CalCOFI stations because of smaller sample size and greater spacing between data points. Station data analyzed using IDW included zooplankton displacement volumes and CTD bottle temperature data for cruises 0701, 0801, and 0803. To ensure that the different interpolations produced similar contour maps for underway data and station data, we downsampled underway SST data for four cruises (one each season) at intervals mimicking station spacing, and compared the IDW and Kriging products by performing a paired Student *t*-test (Sokal and Rohlf 2001) using surface temperatures extracted at random locations from each coverage. The results were not statistically significant and we proceeded with IDW analysis of bottle SST for the three cruises for which underway data were unavailable.

Whale sighting locations recorded while observers were on effort were overlaid onto zooplankton displacement volume and SST coverages to produce contour maps for each cruise. Line segments representing visual search effort were constructed and depicted on contour maps. Zooplankton displacement volume and SST were extracted for each whale sighting location for each cruise. We pooled these interpolated zooplankton and SST values by season and compared the values at whale sighting locations to those at the same number of random locations generated along survey effort tracklines, using a nonparametric Mann-Whitney U test for $n > 20$ (Sokal and Rolf 2001).

TABLE 1
Large baleen whale sightings, combined by season, in CalCOFI southern California region (lines 93 through 77), July 2004–March 2008.

	Winter	Spring	Summer	Fall	Total
Blue Whale	0	0	31	5	36
Fin Whale	3	4	23	22	52
Humpback Whale	0	13	36	18	67
Unidentified Baleen Whale	22	10	54	51	137
Total	25	27	144	96	**292**

RESULTS

The sighting rates of blue, fin, and humpback whales varied seasonally and spatially. The number of large baleen whale sightings (including unidentified to species) was greatest in summer and fall (tab. 1). Blue and humpback whale sightings were most frequent during summer cruises (July–August); fin whales were seen with almost equal frequency in summer and fall (October–November). Blue whales were not seen in winter (January–February) or spring (March–April), whereas fin whales were observed year-round and humpback whales were frequently seen in spring and fall. Unidentified baleen whale sightings accounted for about 38% of the total sightings in spring and summer, 53% in fall, and 88% in winter (tab. 1). Humpback whale sightings were predominantly on the shelf (<2000 m depth; see fig. 1), concentrated near Point Conception and the Channel Islands, whereas blue and fin whale distributions extended further offshore (fig. 2). Douglas et al.[1] provide a more detailed analysis of cetacean seasonality and inshore/offshore patterns observed during CalCOFI cruises.

Winter baleen whale sightings, predominantly unidentified and fin whales, were sparse and occurred both inshore and offshore (of the 2000 m isobath) (fig. 2A). Winter and spring were characterized by cold SST and low zooplankton biomass throughout most of the study area (fig. 2A, B). Winter whale distributions did not differ noticeably between years. During spring, SSTs remained cold overall, with the coldest temperatures generally in the nearshore region from Point Conception to the northern Channel Islands, although cold temperatures extended further offshore in 2007 and 2008 (fig. 2B). Zooplankton biomass increased somewhat in spring relative to winter and the greatest displacement volumes were generally along the coast (fig. 2B). Nearly all whale sightings that took place in spring were inshore, again with no noticeable interannual variation, particularly given the reduced survey effort in spring 2007 and 2008 (fig. 2B).

Summer whale sightings were associated with elevated zooplankton levels, which corresponded to cold SSTs near Point Conception and to the south (fig. 2C). Cold surface water within the central CalCOFI area was

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[3] Amy Hays. pers. commun. NOAA Fisheries Southwest Fisheries Science Center. 3333 Torrey Pines Road, La Jolla, California 92037.

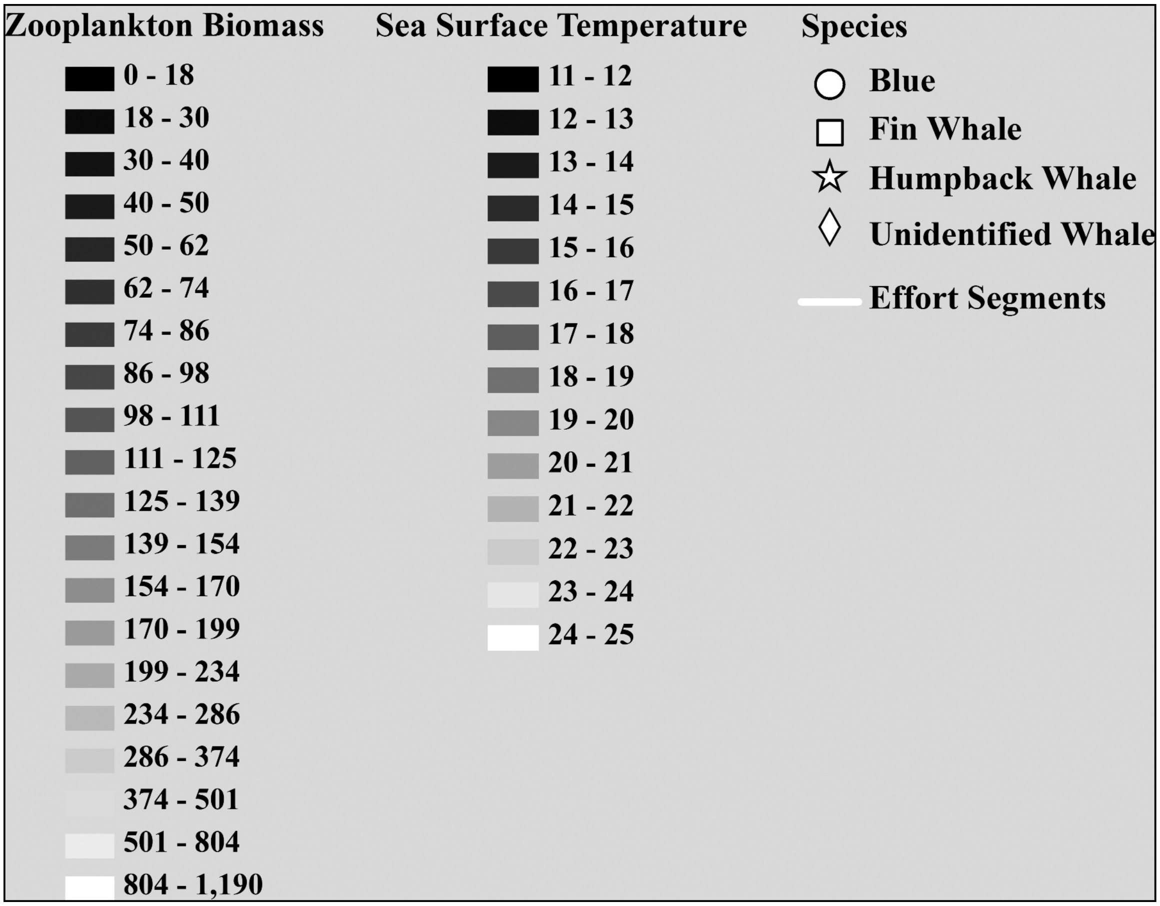


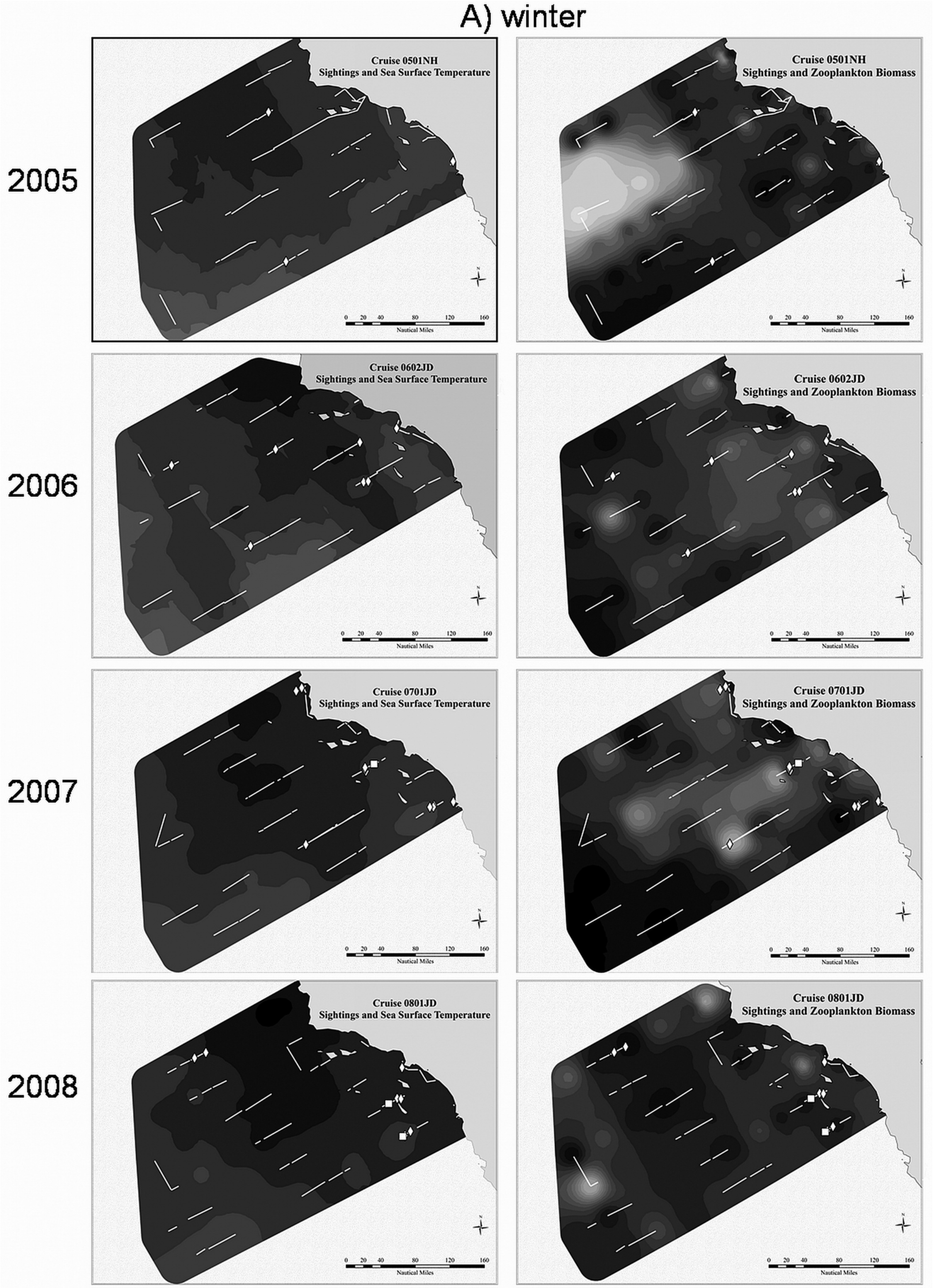
Figure 2. Legend: Zooplankton biomass = total zooplankton displacement volume, ml/1000 m^3 strained. Sea surface temperature in degrees Celsius. Following four pages: Whale sightings overlaid on contour maps of SST (left) and zooplankton biomass (right), A) winter cruises, 2005–2008, B) spring cruises, 2005–2008, C) summer cruises, 2004–2007, D) fall cruises, 2004–2007.

centered further offshore in summer than in spring, just seaward of the Channel Islands. In summer 2004, zooplankton abundance was high throughout the central part of the study area; this was reflected by more dispersed, offshore whale sightings (fig. 2C). In contrast, whale sightings in 2007 were clustered around Point Conception, where zooplankton abundance was greatest and more tightly restricted. The Southern California Countercurrent was also strongest in summer (Hickey 1979, 1992; Lynn and Simpson 1987), resulting in warm coastal water and lower zooplankton levels in the southeastern portion of the bight; however, several whale sightings (blue and unidentified whales) occurred along the southern California coast in 2006 and 2007 (fig. 2C). Blue and fin whale summer distributions included both southern (87–93) and northern (77–83) lines, whereas humpbacks were only seen north of line 83 during summer cruises (fig. 2C).

In fall, SSTs remained warm throughout much of the study area (fig. 2D). Fall zooplankton displacement volumes were low overall (see Goericke et al. 2005, 2007; Peterson et al. 2006; McClatchie et al. 2008) and whale sightings occurred primarily in cool water near shore and islands, with some scattered sightings offshore on southern lines. During three of the four fall cruises, a cluster of blue and fin (2004, 2005) or unidentified whales (2007) were sighted offshore along lines 77 and 80 (fig. 2D). A southward transit along the outer Channel Islands in fall 2006 resulted in numerous sightings, but was not repeated in other cruises and cannot be compared with other seasons or years.

Average SST at whale sightings in summer through fall was colder than the average from random locations along effort trackline, with the greatest difference in summer (fig. 3A). The exception to this was in summer 2006, when the mean SST at whale sightings was almost 1°C greater than average from random locations. Summer whale sighting locations also corresponded to greater zooplankton displacement volumes on average more than to random locations (fig. 3B). Most of the winter and spring data points in Figure 3 are based on small sample sizes (number of sightings < 10).

Pooling data by season showed significant differences in median SST and zooplankton displacement volumes


A) winter
2005
Cruise 0501NH
Sightings and Sea Surface Temperature
Cruise 0501NH
Sightings and Zooplankton Biomass
2006
Cruise 0602JD
Sightings and Sea Surface Temperature
Cruise 0602JD
Sightings and Zooplankton Biomass
2007
Cruise 0701JD
Sightings and Sea Surface Temperature
Cruise 0701JD
Sightings and Zooplankton Biomass
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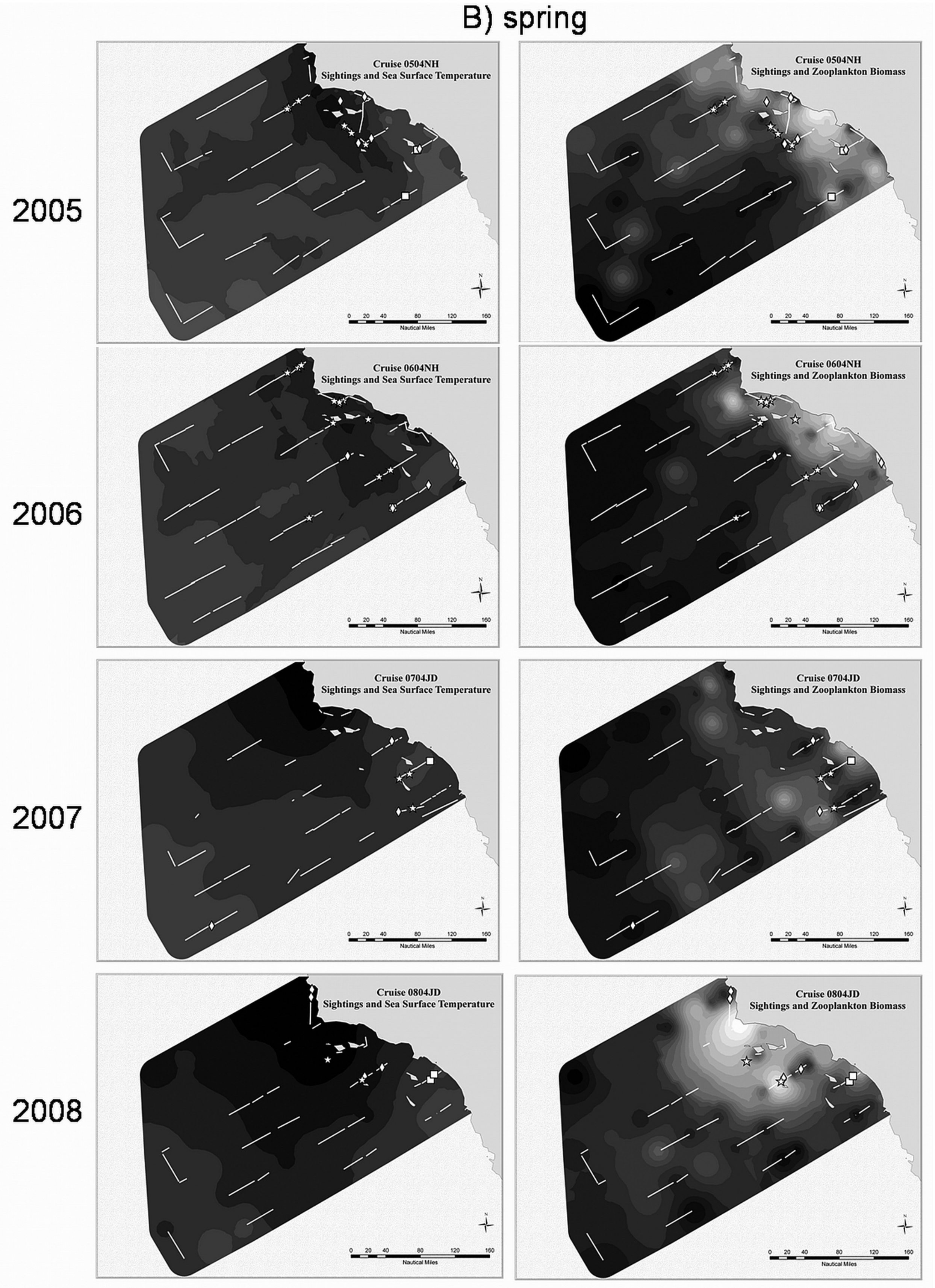
B) spring
2005
Cruise 0504NH
Sightings and Sea Surface Temperature
Cruise 0504NH
Sightings and Zooplankton Biomass
2006
Cruise 0604NH
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Cruise 0604NH
Sightings and Zooplankton Biomass
2007
Cruise 0704JD
Sightings and Sea Surface Temperature
Cruise 0704JD
Sightings and Zooplankton Biomass
2008
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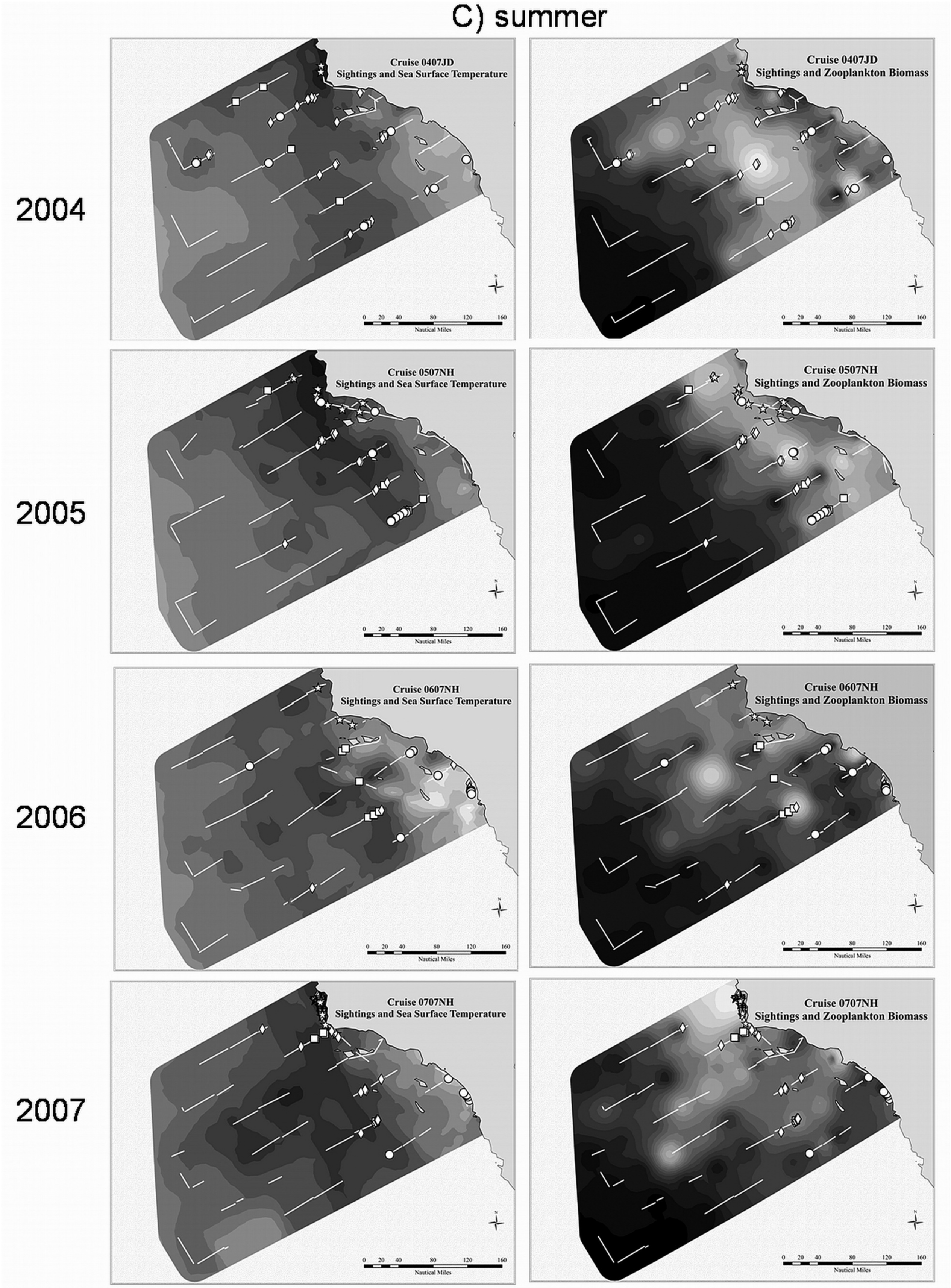
Nautical Miles


C) summer
2004
Cruise 0407JD
Sightings and Sea Surface Temperature
Cruise 0407JD
Sightings and Zooplankton Biomass
2005
Cruise 0507NH
Sightings and Sea Surface Temperature
Cruise 0507NH
Sightings and Zooplankton Biomass
2006
Cruise 0607NH
Sightings and Sea Surface Temperature
Cruise 0607NH
Sightings and Zooplankton Biomass
2007
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Cruise 0707NH
Sightings and Zooplankton Biomass
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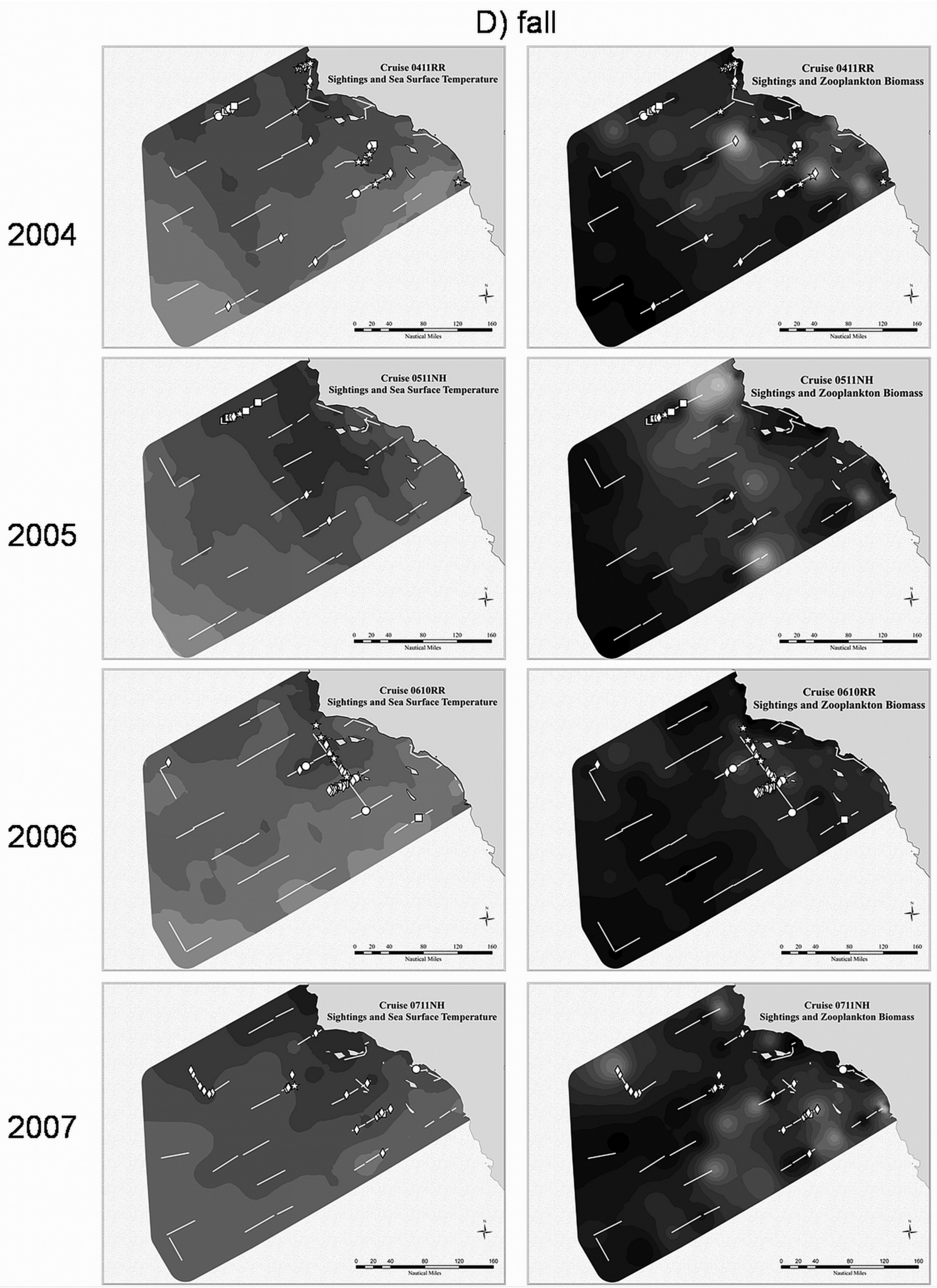
D) fall
2004
2005
2006
2007
Cruise 0411RR
Sightings and Sea Surface Temperature
Cruise 0411RR
Sightings and Zooplankton Biomass
Cruise 0511NH
Sightings and Sea Surface Temperature
Cruise 0511NH
Sightings and Zooplankton Biomass
Cruise 0610RR
Sightings and Sea Surface Temperature
Cruise 0610RR
Sightings and Zooplankton Biomass
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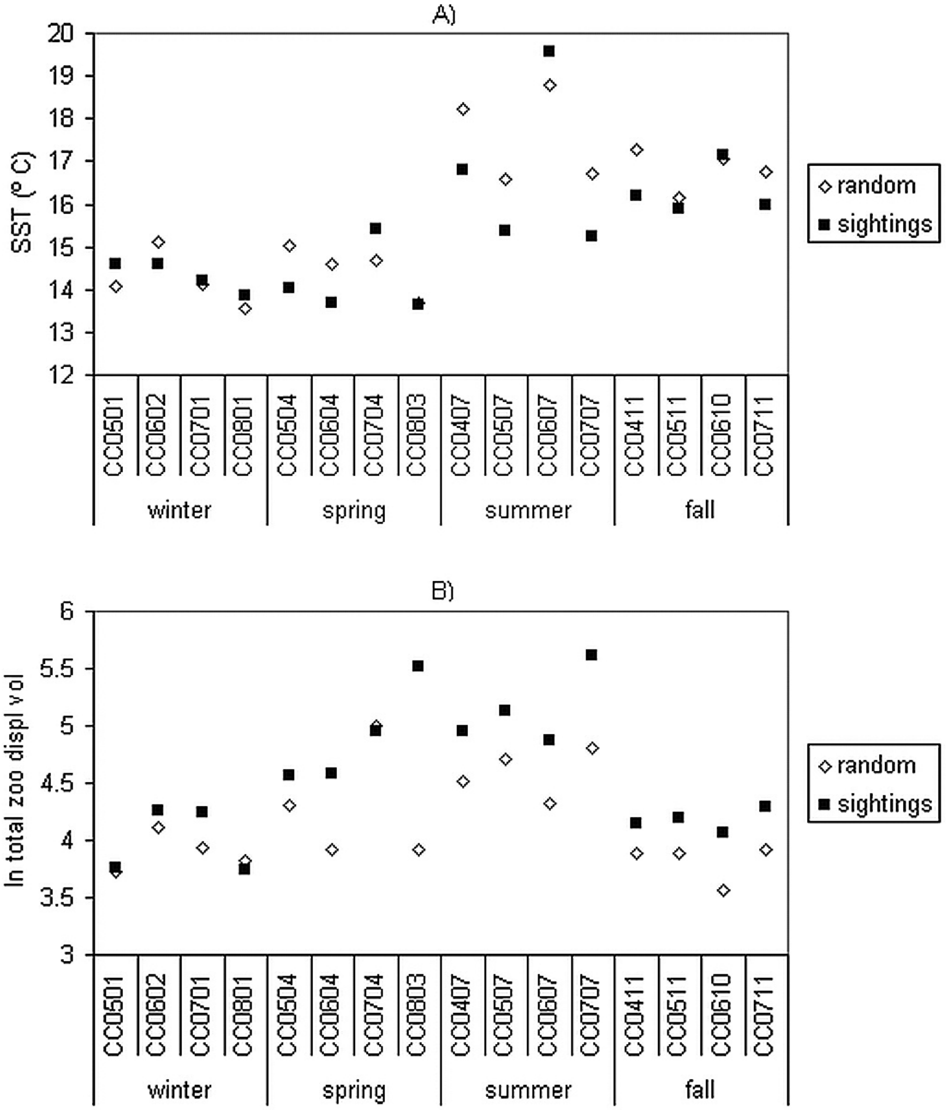

Figure 3. A) Mean SST for random locations along effort trackline (open diamonds) and at whale sightings (filled squares). B) Natural logarithm of mean total zooplankton displacement volume at random locations and whale sightings.

at whale sightings compared to random trackline locations in spring, summer, and fall, but not winter (fig. 4). Relevant statistical quantities are given in Table 2.

DISCUSSION

The summer peak in large whale sightings and their association with high zooplankton displacement volumes during that time indicate that blue, fin, and humpback whales use the Southern California Bight (SCB) primarily as summer foraging habitat, consistent with historic and recent observations (Forney and Barlow 1998; Fiedler et al. 1998a; Barlow and Forney 2007). However, fin whales and unidentified large whales were present year-round in the SCB, with a more scattered offshore distribution in winter. These findings are not new; how-

TABLE 2

Summary of Mann-Whitney U test results comparing SST and zooplankton volumes extracted at whale sightings to random locations (number of random locations equal to number of sightings), pooled by season.

Season	Variable	*n*	Sum of ranks	t_s (Mann-Whitney U-test, *n* > 20)	*p*-value
Winter	SST	25	624	−0.252	0.801
Winter	Zooplankton Vol	25	611	−0.505	0.614
Spring	SST	27	904	2.785	< 0.01
Spring	Zooplankton Vol	27	526	−3.737	<< 0.01
Summer	SST	144	24394	5.074	<< 0.01
Summer	Zooplankton Vol	144	15309	−7.781	<< 0.01
Fall	SST	96	10438	3.048	< 0.01
Fall	Zooplankton Vol	96	7234.5	−5.270	<< 0.01

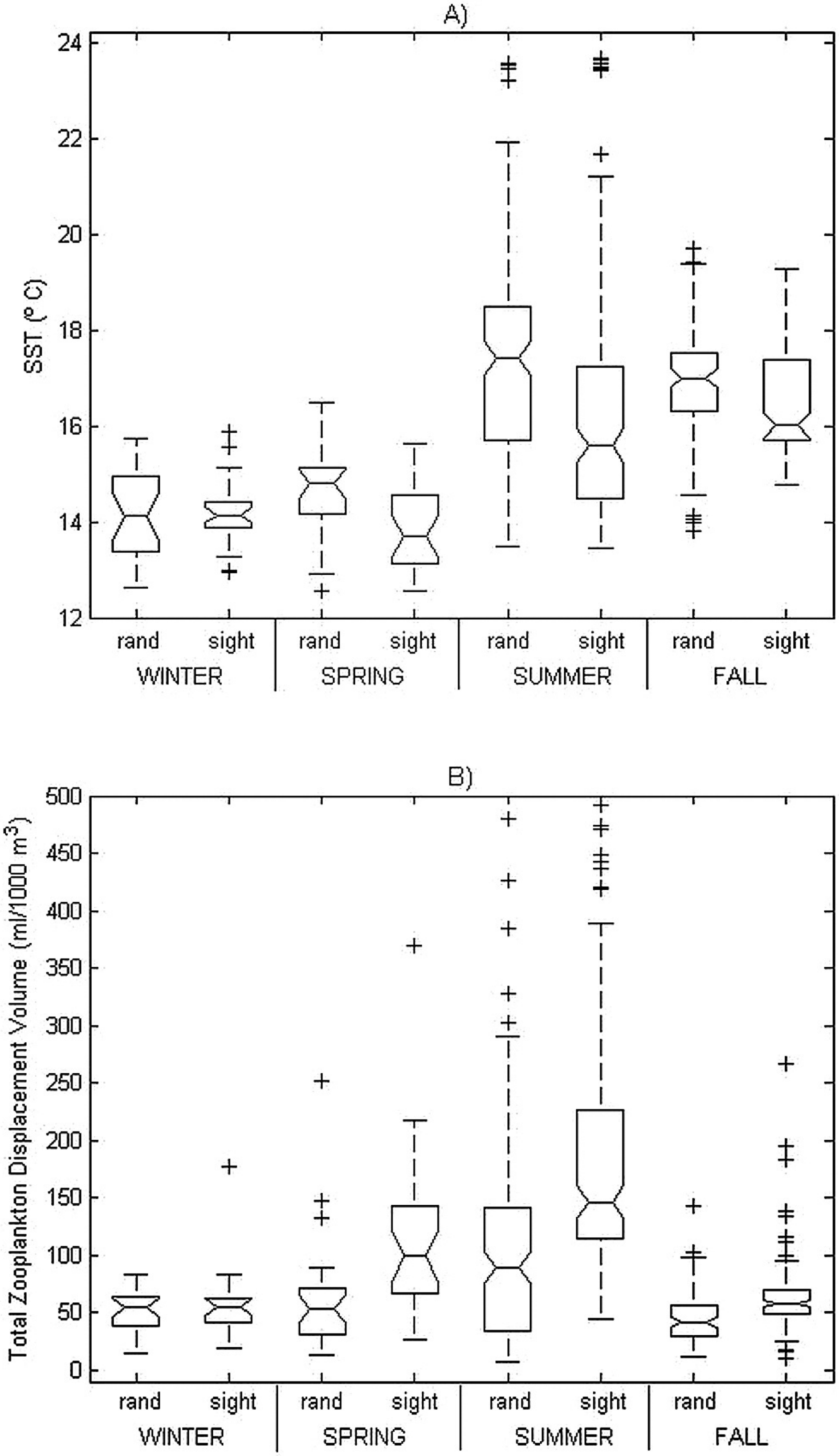

Figure 4. Notched box plots showing lower quartile, median, and upper quartile values of A) SST and B) zooplankton displacement volumes at random locations (rand) and whale sightings (sight). No overlap in notches indicates significant difference ($p < 0.05$) between medians. Dashed whiskers show extent of data to 1.5 times the interquartile range. In plot B (zooplankton), five outliers (plus symbols) > 500 ml/1000 m^3 in summer not shown.

ever, they reflect more recent (2004–08), ongoing, and repetitive seasonal effort than broad-scale, population assessment surveys to date (e.g. Forney and Barlow 1998; Barlow and Forney 2007).

The high proportion of unidentified sightings in winter may be related to generally poorer sighting conditions, i.e. weather and sea state, during that time of year, particularly in the offshore region. Although weather and sea conditions are typically at their worst in spring, most sightings were close to shore or islands and potentially were in relatively calmer water. Unidentified winter and spring sightings were likely to include fin whales and humpbacks as they have been visually and acoustically detected off California during those times of year (Forney and Barlow 1998; Norris et al. 1999; Oleson 2005), whereas blue whales were only rarely detected in early winter and late spring (Oleson et al. 2007).

In summer, whale sightings were generally associated with high zooplankton displacement volumes and cold surface water. The exception to this was during summer 2006, when surface temperatures were warm inshore throughout the SCB and whale sightings were in warmer-than-average surface water. Although the overall zooplankton abundance in summer 2006 was lower than usual, perhaps due to delayed and weak upwelling (Goericke et al. 2007), whale sightings were nonetheless associated with greater than cruise-average zooplankton displacement volumes. The general pattern of whales and zooplankton being associated with cold surface temperatures or gradients in SST may be indicative of conditions leading to zooplankton production, e.g., upwelling and advection of cold, nutrient-rich water, or mechanisms that entrain and concentrate zooplankton, such as fronts and eddies.

The macrozooplankton sampling and analysis methods were not specifically geared toward measuring krill abundance, and several caveats apply when drawing associations between total zooplankton displacement volumes and whale foraging conditions. Net samples were not sorted to taxon as of this study, and may have included some gelatinous organisms as well as prey items such as copepods and euphausiids. We attempted to exclude samples that likely contained abundant gelatinous organisms based on our communication with scientists who had collected samples, but presence of gelatinous organisms in the remaining data could have skewed total zooplankton biomass volumes to appear richer in potential prey than they really were. In addition, sighting data and random points for comparison both occurred only during daytime. Krill are therefore likely to have been underrepresented in total macrozooplankton biomass due to their capability to avoid nets, particularly in daylight, and potential for vertically-migrating krill and other crustaceans to be concentrated during the day at greater depth than net deployments (Brinton 1967; Everson and Bone 1986; Ianson et al. 2004). Finally, whale observation effort and zooplankton sampling did not take place on exactly the same scales. Visual search efforts were conducted while in transit, whereas zooplankton sampling took place at stations 37 or 74 km apart and therefore may have missed zooplankton patchiness on finer spatial scales. A better method for estimating euphausiid densities may be to measure acoustic backscatter near-continuously (Sameoto et al. 1993; Fiedler et al. 1998b; Fielding et al. 2004). Acoustic backscatter was not measured by the RV *New Horizon*, which conducted most of the summer cruises, although backscatter data at some frequencies were collected on other cruises by the RVs *David Starr Jordan* and *Roger Revelle*. In winter 2009, a Simrad EK-60 acoustic echosounder was installed on the RV *New Horizon*, and will enable better characterization of euphausiid densities with greater spatial resolution.

During the past two decades, populations of baleen whales that forage or migrate in the California Current Ecosystem have increased and/or continue to increase (Calambokidis and Barlow 2004; Barlow and Forney 2007). At the same time, average total zooplankton displacement volumes (per CalCOFI cruise) off California have been declining from 1984–98 and 1999–present levels (Goericke et al. 2007; McClatchie et al. 2008). Shifts in whale distribution may be partly in response to such trends in zooplankton availability. For example, blue whales, abundant around the Channel Islands in the 1990s (Fiedler et al. 1998a), have been decreasing in density off southern California since 1997 (Barlow and Forney 2007). This is likely due to redistribution of animals that previously fed off California, potentially to more northerly feeding areas off British Columbia and in the Gulf of Alaska (Barlow et al. 2008a, Calambokidis et al. 2009), or southward to habitats off Baja California (Calambokidis et al. 1990; Tershy et al. 1990; Rice 1974) or Central America (Wade and Friedrichsen 1979; Reilly and Thayer 1990; Wade and Gerrodette 1993). During the CalCOFI cruises in 2005, fin whales were seen more frequently in northern offshore areas than in the 1990s, and blue whales were more dispersed northward along the U.S. west coast (Peterson et al. 2006), perhaps also related to prey distribution. Barlow et al. 2008b calculated that at their currently estimated abundance, baleen whales in the California Current Ecosystem require about 4% of the net primary production to sustain the prey that they consume. As cetacean populations continue to increase, it will be of value to understand how climate variability and long-term trends affect primary production, as well as the mechanisms that lead to secondary production and prey concentration within the CCE.

This study was mainly descriptive, rather than quantitative, as a first step toward using CalCOFI data to examine patterns in large baleen whale distributions and marine ecosystem variables off southern California. Based on these results, we hypothesize that large baleen whale distributions are negatively correlated with sea surface temperature and positively correlated with zooplankton biomass during foraging season. We also hypothesize that whale foraging distributions off southern California shift depending on location and temporal shifts therein of the California Current and coastal upwelling centers. Some recurring high densities of whale sightings, such as offshore on northern lines (77–80) in fall, are not clearly related to either of the variables mapped in this study, and warrant further examination. Analyses are underway to investigate CalCOFI cetacean diversity and encounter rates in relation to season, depth, and distance to shore and shelf break (Douglas et al.[1]). Subsequent analyses should incorporate additional environmental variables, including remotely-sensed data as well as in situ measurements, to elucidate habitat use using more rigorous statistical techniques and potentially to aid in estimating whale densities (de Segura et al. 2007). Including acoustic backscatter measurements of prey density on future cruises will also provide a more direct link for examining whale responses to habitat variation.

CONCLUSIONS

Habitat models are a useful tool for understanding how whales interact with dynamic marine ecosystems and respond to prey patchiness and temporal variability. Federally-sponsored marine mammal surveys off California are designed to estimate population abundance over their entire seasonal range, and are conducted primarily in summer and fall every three to five years over a broad area spanning the U.S. west coast (Barlow and Forney 2007; Forney and Barlow 1998). In contrast, CalCOFI provides a platform to observe marine mammals at a smaller geographic scale with greater temporal resolution. As of the submission of this manuscript, marine mammal surveys have been conducted on 20 CalCOFI cruises since 2004, and the number of CalCOFI baleen whale sightings is beginning to exceed those reported in the southern California region in NMFS population assessment surveys for some species (*e.g.*, for humpback whales). Augmenting the CalCOFI marine mammal time series and increase sighting sample size by continuing marine mammal observations aboard seasonal CalCOFI cruises will improve our understanding of whale habitat use off southern California and allow us to test predictions about whale occurrence in relation to different oceanographic variables. Southern California marine ecosystems are affected by a variety of human uses (shipping, fishing, military, industrial, etc.), and predictive models of whale distribution may become a valuable management tool for whale populations with whom we share this productive and complex ecosystem.

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UNUSUAL OCCURRENCE OF A GREEN STURGEON, *ACIPENSER MEDIROSTRIS*, AT EL SOCORRO, BAJA CALIFORNIA, MÉXICO

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ABSTRACT

In December 2008, a green sturgeon (*Acipenser medirostris*) occurred 200 km south of Bahía de Todos Santos, Baja California (México), the southern limit of its known distribution. This green sturgeon (152 cm total length, TL) is the first documented northwest of Baja California in 27 years of samplings. The movement southward was possibly in response to the 2008 La Niña conditions that prevailed in the California Current.

INTRODUCTION

The green sturgeon, *Acipenser medirostris* (Ayers 1854), was named "medirostris" or "middle snout" due to its long rostrum compared to other sturgeon species. It is anadromous and lives primarily in marine waters, benthic and long-lived inhabiting shallow sand and mud bottoms (Love 1996), and spawns in shallow freshwater (Erickson et al. 2002). Distribution of the green sturgeon ranges from Ensenada, Baja California (México), to the Bering Sea and Japan (Miller and Lea 1972). It is now considered a different species from the Sakhalin sturgeon (*A. mikadoi*) present in Japan (Erickson et al. 2002). The green sturgeon is divided into two genetically distinct breeding populations, a northern distinct population segment (DPS) that spawns in the Rogue River (Oregon), Klamath River and Eel River (California), and a southern DPS that spawns in the Sacramento River, California (Klimley et al. 2007). Spawning

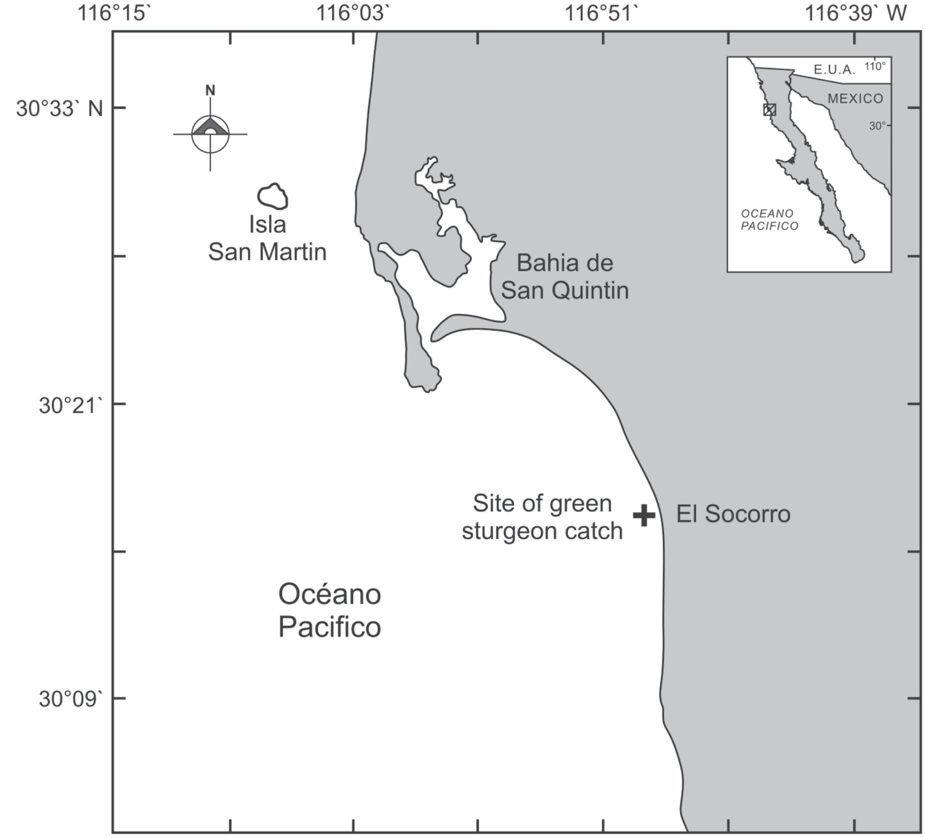

Figure 1. Map of the El Socorro coast in Baja California, México, showing the catch site of the green sturgeon (*Acipenser medirostris*).

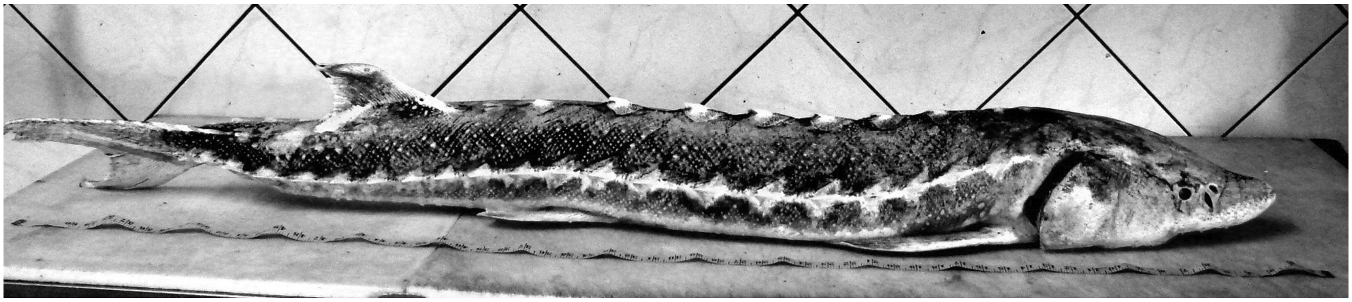

Figure 2. Green sturgeon (*Acipenser medirostris*) caught off the El Socorro coast. Measuring tape (bottom) is 160 cm length.

areas of the southern DPS green sturgeon have been lost due to the Shasta dam construction on the Sacramento River. This DPS now has to spawn outside of its natural habitat, increasing its vulnerability to overharvesting (Adams et al. 2007). The southern DPS is listed as threatened under the Endangered Species Act (Adams et al. 2007).

METHODS

A green sturgeon was captured with a commercial gillnet (17 December 2008) on the El Socorro coast (30°17'12.6N, 115°49'12.6W) located 30 km south of San Quintín, Baja California, México (fig. 1), and 200 km south of Ensenada, Baja California (Bahía de Todos Santos, 31°48.5'N, 116°42'W), its known southern distribution limit (Miller and Lea 1972; Love 1996). Surface-water temperatures at the site were 16.1°–17.7°C. This fish was 152 cm total length (TL) with a somatic weight of 19 kg, and it was identified as green sturgeon by the combination of the following characteristics (Miller and Lea 1972): body coloration was olive green; dorsal plates: eight; midlateral plates: 23; ventral plates: eight; dorsal fin rays: 33; and anal fin rays: 22. Four barbells were located in front and close to the mouth (fig. 2). All these characteristics distinguish and separate it from the white sturgeon (*A. transmontanus*), another species whose southern distribution is Bahía de Todos Santos.

Fish studies at Bahía de Todos Santos began in 1982 in the Estero de Punta Banda (Beltrán-Félix et al. 1986) in kelp beds (Díaz-Díaz and Hammann 1987), soft bottoms (Hammann and Rosales-Casián 1990), and from the sportfishing catch (Rodriguez-Medrano 1993). Other fish-community research has been conducted at Bahía de Todos Santos, and Bahía and Costa de San Quintín (1992–95), with beam trawl, otter trawl, beach seine, gillnet, and hook-and-line trawls (Rosales-Casián 1997a,b; Rosales-Casián 2004a). Also, artisanal fisheries were sampled at eight sites along the northwestern coast of Baja California (Rosales-Casián and Gonzalez-Camacho 2003). No sturgeon was collected during those studies. However, during an ongoing study at the seafood market in Ensenada (15 March 2003), a male white sturgeon captured at Bahía de Todos Santos was registered (Rosales-Casián and Ruz-Cruz 2005).

CONCLUSIONS

With respect to the green sturgeon, its unusual occurrence at El Socorro, Baja California, México, is important because this extends its geographical range 200 km to the south. Its presence there may be due to the 2008 La Niña conditions that prevailed in the California Current (McClatchie et al. 2008). Northern fish species can migrate southward during La Niña, in a similar way to movements of tropical species northward during El Niño conditions (Pondella and Allen 2001; Rosales-Casián 2004b).

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BIOACCUMULATION OF MERCURY IN PELAGIC SHARKS FROM THE NORTHEAST PACIFIC OCEAN

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ABSTRACT

The common thresher, *Alopias vulpinus*, and shortfin mako, *Isurus oxyrinchus*, are large pelagic shark species frequently targeted by sport and commercial fisheries. Being top marine predators, the common thresher and shortfin mako are susceptible to bioaccumulation of heavy elements in their tissues. We investigated the levels of mercury (Hg) in the tissues of these sharks from the central and eastern North Pacific Ocean and how those levels reflect their feeding ecology. For both species we found detectable levels of Hg in the white muscle but not in the liver, and no differences in Hg levels between the sexes, which suggests similar feeding patterns. There was, however, a significant interspecific difference with the shortfin mako having considerably higher Hg levels than the common thresher. This likely reflects the shortfin mako's opportunistic feeding on higher trophic level prey, such as jumbo squid (*Dosidicus gigas*), relative to the common thresher which primarily targets smaller schooling fish. We found strong linear relationships between body size and Hg level for both species with a significantly greater rate of increase for the shortfin mako which also may suggest a higher daily ration. In all common thresher samples, Hg levels were well below the U.S. Food and Drug Administration's established action level of 1.0 μg/g for commercial fish. Nearly all shortfin mako muscle samples from sharks ≤150 cm fork length (FL) had Hg levels below 1.0 μg/g, but all shortfin mako >150 cm FL had muscle Hg levels exceeding this level, with the largest sharks having nearly three times this level.

INTRODUCTION

The common thresher, *Alopias vulpinus*, and the shortfin mako, *Isurus oxyrinchus,* are active, strong-swimming endothermic pelagic sharks within the order Lamniformes, the mackerel sharks (Compagno 1984; Smith et al. 2008). The common thresher occurs throughout the temperate northeast Pacific Ocean with all sizes occurring typically within 72–135 km of land (Smith et al. 2008). The shortfin mako also occurs throughout the temperate and tropical northeast Pacific Ocean with juvenile and sub-adult sharks occurring inshore while larger sharks occur further offshore (Compagno 2001). Off the California coast, the common thresher feeds mostly on small schooling fish and cephalopods (Preti et al. 2001) while the shortfin mako is thought to be more opportunistic and mainly preys on a large variety of cephalopods and fish, with some large adults preying on marine mammals (PFMC 2003). Thus, both species represent large predators in the marine food web but with slightly different foraging ecologies, which may affect mercury (Hg) bioaccumulation.

Having high market values, both the common thresher and shortfin mako are harvested by commercial fisheries along the coast of California (Holts et al. 1998: Compagno 2001). Highly regarded as sport fish, they are also targeted by anglers in southern California. A seasonal California drift gillnet fishery for broadbill swordfish, *Xiphias gladius*, lands large numbers of these sharks, which are considered secondary targets (Smith and Aseltine-Neilson 2001; Taylor and Bedford 2001). In 2006, U.S. West Coast commercial fisheries landed 159 mt of common thresher and 46 mt of shortfin mako (PFMC 2007). No reliable landings data are available for the recreational catch.

The high trophic positions and market value of these sharks suggest that it would be worthwhile to determine their mercury levels. Environmental levels of Hg, a toxic metal with no known essential function in vertebrates, have increased dramatically since the onset of the Industrial Revolution. Current anthropogenic activities are estimated to account for about 66% of all the mercury released into the environment annually (Wiener and Spry 1996; Jackson 1997; Downs and Lester 1998). In the marine environment, methylation processes by microorganisms convert inorganic Hg into the more toxic methylmercury (MeHg) (Beckvar et al. 1996; Wiener and Spry 1996). MeHg bioaccumulates in fish, marine mammals and birds due to its rapid uptake and slow rate of elimination (Mason et al. 1995). Studies have shown that high trophic-level fish, such as sharks (Marcovecchio et al. 1991; Hueter et al. 1995), billfishes (Monteiro and Lopes 1990), tunas (Storelli and Marcotrigiano 2004) and large mackerels (Meaburn 1978[1]) are particularly prone to bioaccumulate relatively

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[1] G. M. Meaburn. 1978. Heavy metal contamination of Spanish and King mackerel. *In* Proceedings of the mackerel colloquium, March 16, 1978, Charleston, Lab., SEFSC, Charleston, SC. 61–66 pp.

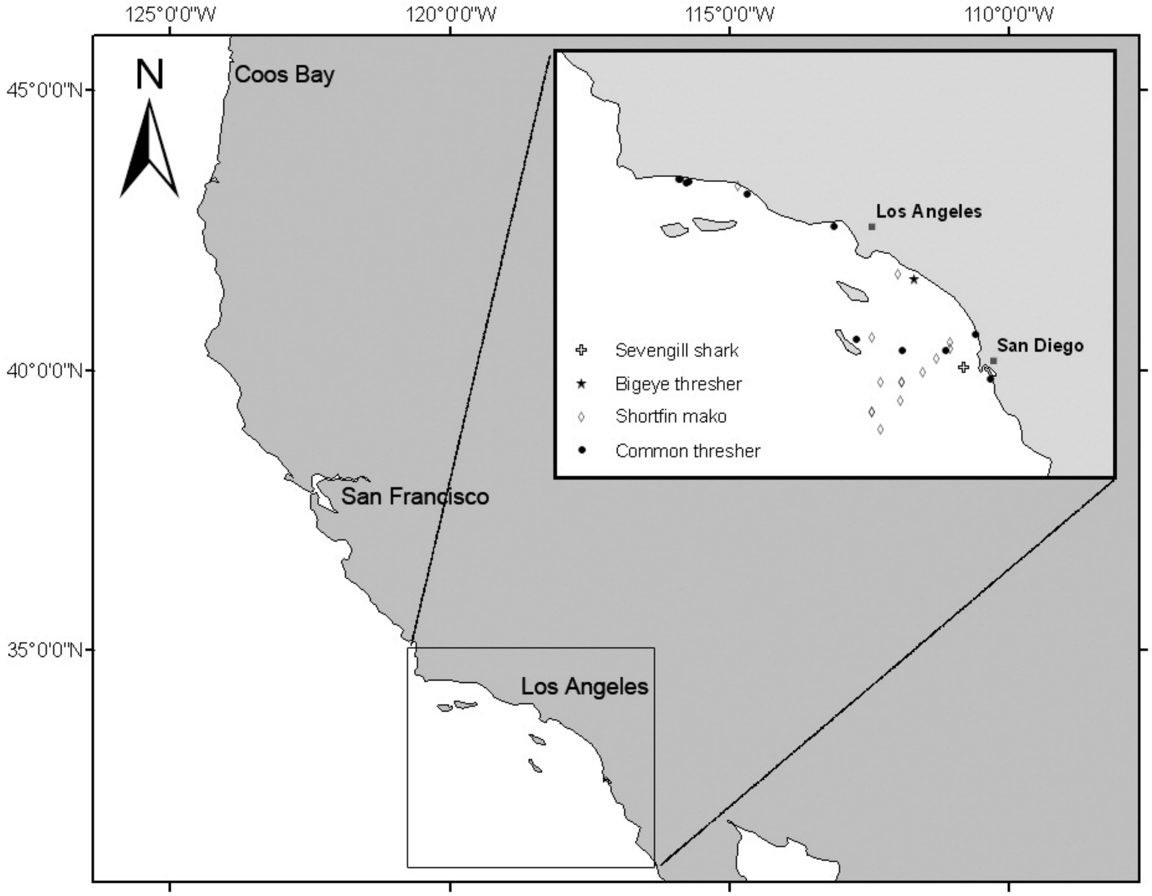

Figure 1. Shortfin mako (*Isurus oxyrinchus*), common thresher (*Alopias vulpinus*), bigeye thresher (*Alopias superciliosus*), and sevengill (*Notorynchus cepedianus*) sample collection locations from the coast of California; expanded image is the Southern California Bight.

high levels of MeHg in their tissues. Thus, the common thresher and shortfin mako may also present a dietary source of Hg to humans.

Despite this, data on Hg levels in these two species are limited or nonexistent and no data are available for the northeast Pacific Ocean. We found no published studies on the Hg levels in the common thresher. Kaneko and Ralston 2007 examined Hg levels in 10 thresher sharks from the Honolulu fish market but the samples were most likely a combination of the two thresher species that predominantly occur in this region, the pelagic thresher, *A. pelagicus*, and the bigeye thresher, *A. superciliosus* (W. Walsh In prep.[2]). Watling et al. 1981 examined the Hg levels in 19 shortfin mako from South Africa and Kaneko and Ralston 2007 examined 10 shortfin mako from Hawaii. Both found high levels of Hg in the shark muscle (0.59–5.58 µg/g in South Africa and 0.40–3.10 µg/g in Hawaii). How these Hg levels compare to those of shortfin mako from California is unknown. The objectives of this study are to determine the levels of Hg in the common thresher and the shortfin mako from the northeast Pacific Ocean, and investigate their relationships with sex, size and feeding ecology.

METHODS

California sample collection and mercury analysis

Common thresher and shortfin mako tissue samples were collected from the following three sources: (1) NOAA National Marine Fisheries Service (NMFS) fishery observers aboard commercial drift gillnet vessels operating off central to southern California during the August 2004–January 2005 fishing season, hereafter referred to as observer surveys; (2) the NMFS juvenile shark survey in the Southern California Bight during July 2004–August 2004, hereafter referred to as NMFS surveys; and (3) the southern California shark fishing tournaments from July 2005–August 2005, hereafter referred to as tournament surveys (fig. 1).

A total of 38 common thresher and 33 shortfin mako sharks were sampled. Observer survey samples (33 common thresher and 19 shortfin mako) and NMFS survey

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[2] W. Walsh. In prep. Pacific Islands Fisheries Science Center 2570 Dole Street Honolulu, Hawaii 96822.

samples (five common thresher and two shortfin mako) were taken at sea while tournament survey samples (12 shortfin mako) were collected at the docks within six hours of capture. From each shark, white muscle and liver were taken using clean stainless steel instruments. Approximately 100 g of white muscle was collected from a region anterior to the origin of the first dorsal fin. For the liver sample, the posterior tip of the liver was taken. All samples were immediately placed in separate polyethylene bags and were either frozen (observer and NMFS surveys) or kept in an ice cooler (tournament surveys) until transport to the NMFS Southwest Fisheries Science Center in La Jolla, California. Once at NMFS, all samples were stored at –20°C. In the laboratory, subsamples (about 20 g) of each tissue were excised using stainless steel instruments and transferred into pre-cleaned glass vials and kept frozen at –20°C until analysis. For all sharks, body size (fork length, FL) and sex were recorded. Observer and NMFS surveys recorded GPS coordinates for capture locations.

To address whether Hg levels in muscle from different parts of the shark differed, one shortfin mako from the NMFS surveys was sampled from multiple regions. Approximately 100 g of muscle was excised from six different regions as follows: axial muscle as described above, lateral muscle from a region directly forward of the origin of the pectoral fin from each side (left and right), ventral muscle from a region approximately 6 cm posterior from the mouth, caudal muscle from the dorsal precaudal region and vertebral muscle from a region ventral to the vertebrae in the stomach cavity. In addition, two bigeye thresher, *A. superciliosus* were sampled from the NMFS surveys and one sevengill shark, *Notorynchus cepedianus*, was collected from an area <5 nm offshore of San Diego Bay in April 2003. Data from these opportunistically sampled species are not conclusive but are presented here for reference because data for the species are lacking. The bigeye thresher samples were collected in the same manner as described for the NMFS surveys. The sevengill shark was frozen whole and the samples excised at the laboratory in May 2005 as described above for tournament surveys.

Studies have shown that virtually all of the total mercury, >95%, in teleost fish muscle (Hight and Corcoran 1987; Grieb et al. 1990; Bloom 1992) and elasmobranch fish muscle (Branco et al. 2004) is in the form of methylmercury (MeHg). Consequently, the measurement of total Hg has become widely accepted as the standard for regulatory monitoring programs as an accurate approximation of MeHg (Hight and Corcoran 1987; Bloom 1992). Total Hg analyses were conducted using cold-vapor atomic absorption spectrophotometry according to EPA protocol 7471A at Enviromatrix Analytical Inc. in San Diego, California, using a Leeman Labs PS200 II automated mercury analyzer. Quality control measures included standard reference materials, laboratory blanks, duplicate tissue samples and matrix spikes. All data met the data quality objectives specified in the quality control section of EPA SW-846. The method detection limit was 0.005 µg/g. Results are reported as ppm µg/g, by wet weight.

Hawaii sample collection and Hg analysis

Muscle tissue samples from 27 shortfin mako were collected by the State of Hawaii's Department of Health from commercially landed sharks from the United Fishing Agency, Ltd at the Honolulu fish market between May 1991 and October 1992. Muscle samples of about 0.4 kg were collected from an area immediately posterior to the head region and subsequently analyzed for MeHg using standard AOAC methods at the Hawaii State Environmental Laboratory (B. Brooks, pers. comm.[3]). The exact quality control methods used are unknown, thus interpretations of these data were limited to general comparisons with the California samples. As these sharks were fully dressed at sea (i.e. gutted, de-headed and de-finned) sexes and accurate body-size measurements were not available, but each carcass was weighed using certified trade scales to the nearest pound. Estimated total mass of each shark was calculated with a formula used by the Pacific Fisheries Information Network based on observer records and port sampling for this species: TM = 1.45 * DM; where TM = total mass in kg, and DM = dressed mass in kg. Subsequently, TM was converted into body size using the length-weight parameters for the shortfin mako shark presented by Kohler et al. 1996.

Statistical analysis

All analyses were performed using Systat vers. 11.0 (Systat Soft. Inc. Port Richmond, California). Statistical significance was set a priori at $\alpha = 0.05$. We used analysis of covariance (ANCOVA) to test for differences in Hg levels between sexes for the common thresher and shortfin mako. No differences were found for either species ($p = 0.15$, common thresher; $p = 0.79$, shortfin mako). Thus, sexes were combined for further analyses. We used ANCOVA to examine the relationships between Hg levels and body size for the common thresher versus shortfin mako from California. Parametric assumptions were evaluated with probability plots and Bartlett's test for homogeneity of variances (Zar 1998).

RESULTS

A summary of the results from all white muscle samples is provided in Table 1 for all species. The results

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[3] B. Brooks. Pers. commun. Hawaii Dept. of Health 1250 Punchbowl St. Honolulu, HI 96813.

TABLE 1
Hg levels in the white muscle from pelagic sharks from California (CA) and Hawaii (HI).

			Hg (μg/g wet weight)			Fork length (cm)	
Species	Common name	*n*	Range	Mean	Std dev.	Range	Mean
Isurus oxyrinchus (CA)	Shortfin mako	33	0.15–2.90	1.13	0.89	75–330	164
Alopias vulpinus (CA)	Common thresher	38	0.00–0.70	0.13	0.15	63–241	116
Alopias superciliosus (CA)	Bigeye thresher	2	0.46–0.47	0.46	0	178–182	180
Notorynchus cepedianus (CA)	Sevengill shark	1	0.48	—	—	118	—
Isurus oxyrinchus (HI)	Shortfin mako	27	0.40–3.10	1.32	0.68	105–240	185

TABLE 2
Results of the ANCOVA between common thresher (*Alopias vulpinus*) and shortfin mako (*Isurus oxyrinchus*) from California.

Source	SS	df	MS	*F*-ratio	*p*
Species	0.365	1	0.365	6.734	0.01
Fork Length (FL)	8.115	1	8.115	149.789	0.00
Species*FL	3.009	1	3.009	55.549	0.00
Error	3.63	67	0.054		

from the analyses of 15 liver samples (11 common thresher, two shortfin mako and two bigeye thresher) showed no detectable levels of Hg; thus no further liver samples were analyzed. From California, 38 common thresher and 33 shortfin mako were analyzed for Hg in their muscle tissue. Common thresher sizes ranged from 63 to 241 cm FL (tab. 1). Common thresher muscle Hg levels ranged from 0.00 to 0.70 μg/g (tab. 1). California shortfin mako sizes ranged from 75 to 330 cm FL. Shortfin mako muscle Hg levels ranged from 0.15 to 2.90 μg/g. The ANCOVA found a significant difference in the relationship between muscle Hg and FL for the common thresher and shortfin mako (tab. 2). Muscle Hg levels increased with size significantly faster in the shortfin mako relative to the common thresher. Pearson's linear regression was used to describe the relationship between muscle Hg levels and body size for both species ($r^2 = 0.47$, $p = 0.00$, for the common thresher; $r^2 = 0.87$, $p = 0.00$, for the shortfin mako; fig. 2). Multiple muscle samples taken from different regions of a single shortfin mako revealed small differences in Hg levels, mean = 1.23 ± 0.15, range = 1.06–1.48 μg/g, with the axial muscle representative of the other samples and being very close to the mean at 1.16 μg/g.

The two California bigeye threshers measured 178 and 182 cm FL and their muscle Hg levels were 0.46 to 0.47 μg/g, respectively (tab. 1). The one sevengill shark sampled was 118 cm FL and had muscle Hg level of 0.48 μg/g. The Hawaii shortfin mako body sizes calculated from mass ranged from 105–240 cm FL. The muscle Hg levels ranged from 0.40–3.10 μg/g. Due to uncertainties with quality control, regression analysis was not conducted on this dataset.

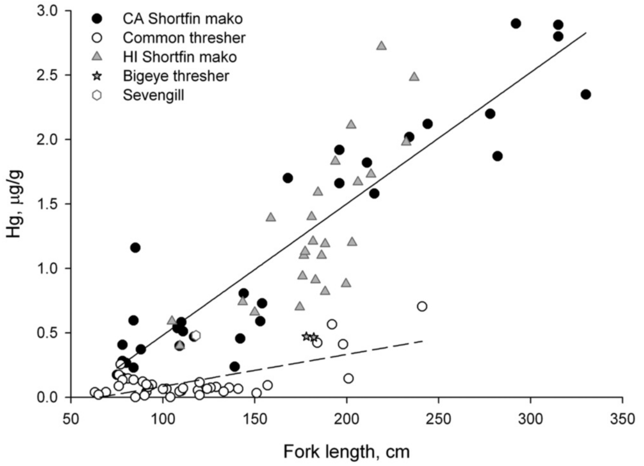

Figure 2. Pelagic shark muscle Hg levels for California (CA) shortfin mako (*Isurus oxyrinchus*), common thresher (*Alopias vulpinus*), Hawaii (HI) shortfin mako, bigeye thresher (*Alopias superciliosus*), and sevengill (*Notorynchus cepedianus*) plotted versus fork length (FL) from California (CA) and Hawaii (HI). Pearson's linear regression for the CA common thresher (dotted line; Hg = 0.0025*FL − 0.1629) and CA shortfin mako shark (solid line; Hg = 0.0102*FL − 0.5376).

DISCUSSION

This represents the first comprehensive study detailing mercury levels in mako and thresher sharks in the eastern North Pacific Ocean. The data provide insight into the influence of sex, size and foraging ecology on mercury levels in commercially important pelagic sharks. The difference in Hg levels between the common thresher and shortfin mako found in this study is largely explained by differences in their feeding ecology and trophic position. The common thresher from California has been shown to feed most heavily on small schooling fish such as the northern anchovy, *Engraulis mordax*, and Pacific sardine, *Sardinops sagax* (Preti et al. 2001). The shortfin mako from California feeds on schooling fish like the Pacific saury, *Cololabis saira*, and cephalopods such as the jumbo squid, *Dosidicus gigas*, revealing opportunistic foraging habits (Preti et al. 2006[4]; Suk 2008). Even at the largest sizes, the common thresher has been

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[4] A. Preti, S. E. Smith, D. A. Ramon, and S. Kohin. 2006. Diet differences among 3 species of pelagic sharks inhabiting the California Current. 57th Tuna Conference, May 22–25, 2006, Lake Arrowhead, CA.

shown to have a considerably lower trophic position relative to the shortfin mako; When comparing animals of a similar size, stable isotope analysis of nitrogen revealed that the common thresher is one-fourth of a trophic position lower than the shortfin mako (Suk 2008). This trophic difference likely explains the generally higher Hg levels found in the shortfin mako. In addition, the shortfin mako, being an extremely active predator, might be expected to have a higher daily ration in comparison to common thresher of the same size. A higher rate of food intake could help explain the much faster increase in Hg levels with increasing body size in the shortfin mako compared to the common thresher from the same region (Stillwell 1990).

The shortfin mako sampled from Hawaii between 1991–92 had a mean Hg level of 1.32 ± 0.68 μg/g in the muscle. These findings are comparable to those of Kaneko and Ralston 2007 who found a mean Hg level of 1.81 ± 0.42 μg/g in 10 shortfin mako from Hawaii in 2006. The observed difference, although not significant, may be attributed to the wider size range of shortfin mako sampled in this study (8.03–107.7 kg DM versus 40.8–80.3 kg DM), though temporal and spatial distinctions cannot be ruled out. The shortfin mako sampled from California and Hawaii exhibited roughly similar patterns of linear increase in muscle Hg levels with increasing body size. Unfortunately, the uncertainty in the quality control methods for the Hawaii samples constrains further interpretations. As shark tagging efforts have documented migratory movement of shortfin mako between Hawaiian and Californian waters (Wraith et al. In prep.[5]) and the Hg elimination rate of fish species is known to be very slow (Mason et al. 1995), this result is not surprising. Since food habit studies of shortfin mako from the Hawaii region are lacking, we can only speculate that there might not be large differences in the feeding habits of the shortfin mako between the two regions or that any differences are overshadowed by the heavy influence of trophic position on the bioaccumulation of Hg in the pelagic environment. Interestingly, muscle Hg levels for the shortfin mako found in this study are also similar to those for shortfin mako from South Africa (Watling et al. 1981), a geographically separate population, where they have been shown to feed heavily on small elasmobranch prey as opposed to teleosts and cephalopods (Cliff et al. 1990). This further suggests minimal spatial differences in Hg levels in highly migratory pelagic fishes in contrast to more resident fishes, where a single point source of Hg could be more influential (Uryu et al. 2001).

The two bigeye thresher collected had essentially identical levels of Hg in their muscle, about 0.46 μg/g. When compared to the other species, the bigeye thresher had similar Hg levels to the adult common thresher but lower Hg levels than the shortfin mako regardless of size. This is likely explained by foraging ecology as well. The bigeye thresher feeds on some of the same prey species as the adult common thresher although its diet also consists largely of barracudinas, (family Paralepididae) and Pacific hake, *Merluccius productus*, rather than small pelagic fish (Preti et al. 2001; Preti et al. 2008; Suk 2008). However, the small sample size prevents drawing further conclusions.

In contrast to Marcovecchio et al. 1991 who found nearly equal Hg levels from both the liver and muscle tissues of the narrownose smooth-hound shark, *Mustelus schmitti*, none of the liver tissue analyzed in this study had detectable levels of Hg. Studies have shown that in fish, Hg binds to the sulfhydryl group (-SH) in protein, which is most prevalent in muscle tissue (Mason et al. 1995). Thus, predictably, Hg was found to be preferentially stored in the muscle of these pelagic sharks. We chose white muscle for this study because it has been shown to be a good indicator of the exposure level of the whole fish and is also what humans typically consume (Prosi 1979). Storelli et al. 1998 found that muscle tissues sampled from different parts of the blackmouth cat shark, *Galeus melastomus*, showed little differences in Hg levels. Likewise, we found little differences in Hg levels in white muscle sampled from different parts of the shortfin mako, although this was from a single specimen. We conclude that the axial muscle tissue sampled in this study accurately represents the potential source of Hg exposure to humans.

All of the common thresher muscle samples in this study had total Hg levels below the U.S. Food and Drug Administration's established action level of 1.00 μg/g for commercial fish. Likewise, all but one shortfin mako ≤150 cm FL had total Hg levels below this level. Since shortfin mako landed by the U.S. West Coast drift gillnet fishery are primarily juveniles (mean ~130 cm FL; PFMC 2003), these fish represent a minimal human health concern. In contrast, all shortfin mako >150 cm FL had muscle Hg levels exceeding 1.00 μg/g, with some of the largest individuals having nearly three times this level (2.90 μg/g). Kaneko and Ralston 2007 found that the shortfin mako is one of the few pelagic fish species to have an elemental excess of Hg relative to selenium, (Se). Selenium has been shown to negate the toxicity of MeHg by binding to it (Raymond and Ralston 2004). Because Se is not likely to be adequate to counter the MeHg in the shortfin makos sampled, this suggests that some larger shortfin mako may indeed pose a human health risk.

In this study, we have shown that levels of Hg in the muscle tissue of pelagic sharks reflect differences in the feeding ecology and demonstrated a strong linear rela-

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[5] J. Wraith. In prep. Southwest Fisheries Science Center 8604 La Jolla Shores Dr. La Jolla, CA 92037.

tionship between body size and Hg levels for both the shortfin mako and common thresher. The bioaccumulation rate of Hg was considerably faster (i.e. at smaller body sizes) in the shortfin mako versus the common thresher and reflects the higher trophic position of the shortfin mako. In addition, these results which indicate levels of Hg relative to body sizes can be potentially used in the assessment of potential human health risk posed by consuming these sharks.

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rcalcofi: ANALYSIS AND VISUALIZATION OF CALCOFI DATA IN R

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ABSTRACT

We developed a package for the R software environment called "**`rcalcofi`**" designed to facilitate analysis and visualization of data related to the California Cooperative Fisheries Investigations program (CalCOFI) and other similar oceanographic data. The major tasks the package is designed to accomplish are to: convert spatial data between the CalCOFI line/station coordinate system and latitude/longitude or other projections; match nominal spatial locations and nearby points within a given radius; create enhanced spatial plots of multivariable or multivariate data using the lattice graphics system; grid data in the CalCOFI coordinate system; and easily download remotely-sensed data for integration into analyses. The package is freely available, and can be downloaded at ftp://swfscftp.noaa.gov/users/eweber/rcalcofi/.

INTRODUCTION

The R software environment (R Development Core Team 2008) is a tool for conducting statistical computing and graphics that is becoming increasingly popular in the fields of ecology, fisheries science, and oceanography, among others. Its freely available source code and active community of scientists contributing extensions to the base functionality of R make it a flexible tool for conducting oceanographic research. The capability to analyze spatial data in a variety of formats (Bivand et al. 2008) and produce publication-quality graphics in R make it an ideal tool for conducting analyses of data collected as part of the California Cooperative Fisheries Investigations (CalCOFI). Here we describe an R package designed to facilitate visualization and analysis of CalCOFI data and other similar oceanographic data. We created the **`rcalcofi`** package because we found during the course of our own research that we wanted to be able to perform several recurring tasks more conveniently than was possible using existing functionality in R. The major tasks that the package is designed to accomplish are to: convert spatial data between the CalCOFI line/station coordinate system and latitude/longitude or other projections; match nominal spatial locations and nearby points within a given radius; create enhanced spatial plots of multivariable or multivariate data using the lattice graphics system; grid data in the CalCOFI coordinate system; and easily download remotely-sensed data for integration into analyses.

In this article, we briefly describe the major functionality of the package; however, we do not attempt to document every detail of package use. The standard package documentation contains descriptions of all functions and options in **`rcalcofi`**, along with examples. Many more examples are contained in the vignette that is included with the package. It can be accessed directly from the "doc" folder of the package (rcalcofi.pdf), or by using the vignette command in R after the package has been installed.

```
> vignette("rcalcofi")
```

The standard documentation and vignette should serve as the primary references for the package. The source code for the package, and binary packages for the Apple OS X®, and Microsoft Windows® operating systems, can be downloaded at ftp://swfscftp.noaa.gov/users/eweber/rcalcofi. Users who are completely new to R may wish to access the Comprehensive R Archive Network (CRAN), www.cran.R-project.org, to view introductory material, documentation, and references pertaining to the general use of R before working with **`rcalcofi`**. Throughout this article the Courier font is used to indicate R package names, command names, or specific R code.

PACKAGE REQUIREMENTS

The general strategy in developing the package was to use as much of the capability of existing R packages as possible, thereby preserving conventions that are familiar to many users and avoiding duplication of effort. Thus, the package has a relatively long list of dependencies. They are the **`fields`** (Furrer et al. 2009), **`grid`** (R Development Core Team 2008), **`lattice`** (Sarkar 2009), **`maptools`** (Lewin-Koh et al. 2009), **`methods`** (R Development Core Team 2008), **`rgdal`** (Keitt et al. 2008), **`sp`** (Pebesma and Bivand 2005), and **`spatstat`** (Baddeley and Turner 2005) packages available from CRAN repositories. The **`rgdal`** package further requires the installation of the Geospatial Data Abstraction

Library and PROJ4 library for projection and transformation of spatial data. We also recommend installing the gshhs shoreline files (Wessels and Smith 1996) so that higher resolution shoreline images can be plotted. The package particularly relies on **`lattice`** graphics and spatial classes provided by the **`sp`** package. In addition to the standard documentation, **`lattice`** and **`sp`** are described in greater detail by Sarkar (2008) and Bivand et al. (2008), respectively.

MAJOR FUNCTIONALITY

Converting To and From the CalCOFI Line/Station Coordinate System

Converting data expressed in CalCOFI line and station coordinates to latitude and longitude is a common task when analyzing or plotting CalCOFI data. The **`rcalcofi`** package contains the function **`station.to.latlon`** to achieve this, and the reverse function **`latlon.to.station`**. These functions accept a matrix or two-column data frame of coordinates and return a matrix of converted coordinates using the algorithm described by Eber and Hewitt (1979). For example, a matrix of CalCOFI coordinates named **`myCalCOFIdata`** could be converted to a matrix of longitudes and latitudes as follows:

```
> station.to.latlon(myCalCOFIdata)
```

We note that repeated conversions between coordinate systems on the same data should be avoided because a small error is introduced with each conversion (cf., Eber and Hewitt 1979). That is, raw location data should probably be retained, and projection done once for each analysis or plot.

A more flexible way to analyze spatial data is to use the spatial classes provided by the **`sp`** package. The **`sp`** package provides methods for projecting, gridding, overlaying, and converting spatial data (possibly with attributes) to and from data frames and matrices. We have adapted these methods in **`rcalcofi`** to treat the CalCOFI coordinate system as if it were any other map projection (e.g., Mercator, stereographic, etc.). Thus, the usual spatial methods can be applied to data associated with CalCOFI lines and stations, and they can be interconverted, imported, and exported using standard methods. The recommended means of working with CalCOFI spatial data is to convert them to an object of a spatial class (e.g., a **`SpatialPointsDataFrame`**), and then manipulate them using **`sp`** methods. In the **`rcalcofi`** package, the projection "**`+proj=calcofi`**" is used to get the means the CalCOFI line/station coordinate system. The hypothetical **`myCalCOFI`** data matrix could be converted to **`SpatialPoints`** and then transformed as follows:

```
> spdata <- SpatialPoints(data.frame
(myCalCOFIdata), CRS("+proj=calcofi"))
> spdata <- spTransform(spdata, CRS
("+proj=longlat"))
```

Converting to a spatial data type will also allow the data to be plotted using the high-level lattice plotting functions in **`rcalcofi`**, which we describe below.

Matching Locations

Another common problem when working with CalCOFI data is that measurements are recorded at locations near a nominal location (e.g., a station) and must be matched to the nominal record for further analysis. The function **`determine.station`** matches points that are within a specified radius of another set of nominal points. For example, a data frame called **`stations`** was created containing the locations of two near-shore core CalCOFI stations (line 76.7, stations 49 and 51; tab. 1). We matched four hypothetical points in a data frame called **`samples`** (tab. 2) to the nearest station within the default 4 km radius using the following call:

```
> determine.station(samples$lon,
samples$lat, stations$lon, stations$lat,
row.names(stations))
```

The result is a vector of row names from the station data:

```
> [1] 1 NA 2 2
```

The vector indicates the first sample point matches to station 1, and the last two points match to station 2 (fig. 1). The second result is an **`NA`**, indicating the second sample point was not located within 4 km of either

TABLE 1

The stations data frame containing the longitude and latitude of two core CalCOFI stations, line 76.7, stations 49 and 51. The four hypothetical sample points listed in Table 2 were matched to these data using the `determine.station` function, as illustrated in Figure 1.

	lon	lat
1	239.222	35.088
2	239.082	35.022

TABLE 2

The samples data frame containing the longitude and latitude of four hypothetical points that are near the CalCOFI stations listed in Table 1. These data were matched where they were within 4 km of a station using the `determine.station` function, as illustrated in Figure 1.

	lon	lat
1	239.205	35.080
2	239.203	35.124
3	239.051	35.020
4	239.082	35.043

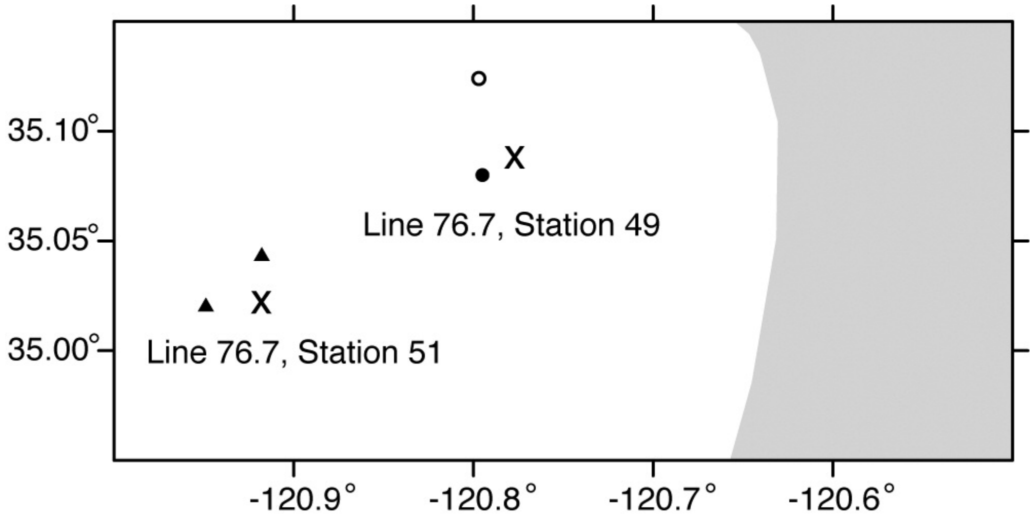

Figure 1. Four hypothetical sample locations (tab. 1) were matched to two core CalCOFI stations, line 76.7, stations 49 and 51 (tab. 2; designated by the "X" symbol), using the `determine.station` function if they were within a 4-km radius of a point. Closed circle indicates a sample location matched to the first station in Table 1 (line 76.7 station 49), and triangles indicate sample locations matched to the second station in Table 1 (line 76.7 station 51). The open circle indicates a location greater than 4 km from either station, so an NA was returned by the function. The gray area represents the shoreline.

of the stations. The resulting vector could be assigned as a column in the **samples** data frame and used to merge data sets using the standard R methods.

Enhanced Plotting of Spatial Data in Lattice

It is often useful to visualize multivariable or multivariate data by constructing graphics with a panel for each level of one or more variables. For example, we frequently plot species abundance separately for each year, or at different levels of one or more environmental variables. The R **lattice** graphics system was designed for plotting these types of data. The **rcalcofi** package adds several high-level lattice functions for plotting spatial data using lattice graphics. These functions have several convenient features for plotting spatial data, including formula methods similar to standard lattice functions, automatic conversion and plotting of spatial data from different projections (including CalCOFI), and default panel functions that were designed to be integrated into more complex graphics. All of the high-level plotting functions in **rcalcofi** accept shoreline maps that can be created easily using the **get.map** function. Nearly all of the standard lattice functions will work as expected with these functions, thereby allowing users who are familiar with lattice graphics to customize plots even further.

The new high-level plotting functions included in **rcalcofi** are **spxyplot**, **splevelplot**, **spcontourplot**, **spgridplot**, and **spstickplot**. The **spxyplot**, **splevelplot**, and **spcontourplot** functions are analogous to the standard lattice **xyplot**, **levelplot**, and **contourplot** functions, except that they accept spatial data types instead of data frames, and plot in any desired projection. The **splevelplot** and **spcontourplot** functions actually call the same underlying function with different options, similar to **levelplot** and **contourplot**. A few other adjustments have been made to **splevelplot** to accommodate data projected from a different coordinate system. If data that were regularly spaced in the original coordinate system are plotted in a different projection, the function will plot polygons with corners at the appropriate projected coordinates rather than rectangles. This is useful for creating a **levelplot** on the CalCOFI grid but plotting it in longitude and latitude, for example. A second option for plotting irregularly-spaced data in **splevelplot** is to use the **krig** option. This will call the **Krig** function (with user arguments, if specified) from the **fields** package to create an interpolated surface, and then plot the surface as a standard **levelplot** in the specified coordinate system.

The **spgridplot** function plots gridded spatial information as a standard grid if it is plotted in its native projection or as a grid with curved lines that reflect distortion if it has been projected to a new coordinate system. It accepts gridded (i.e., regularly spaced) data as objects of gridded spatial classes from the **sp** package (**SpatialGrid**, **SpatialGridDataFrame**, **SpatialPixels**, or **SpatialPixelsDataFrame**).

The **spstickplot** function plots data associated with spatial locations as solid bars or filled frames similar to "thermometers" in the standard graphics **symbols** function. It is useful for creating three-dimensional bar plots.

High-level functions in **rcalcofi** can be called with only one or two arguments for basic use. For example, a **SpatialPoints** object named **mySpatialPoints**

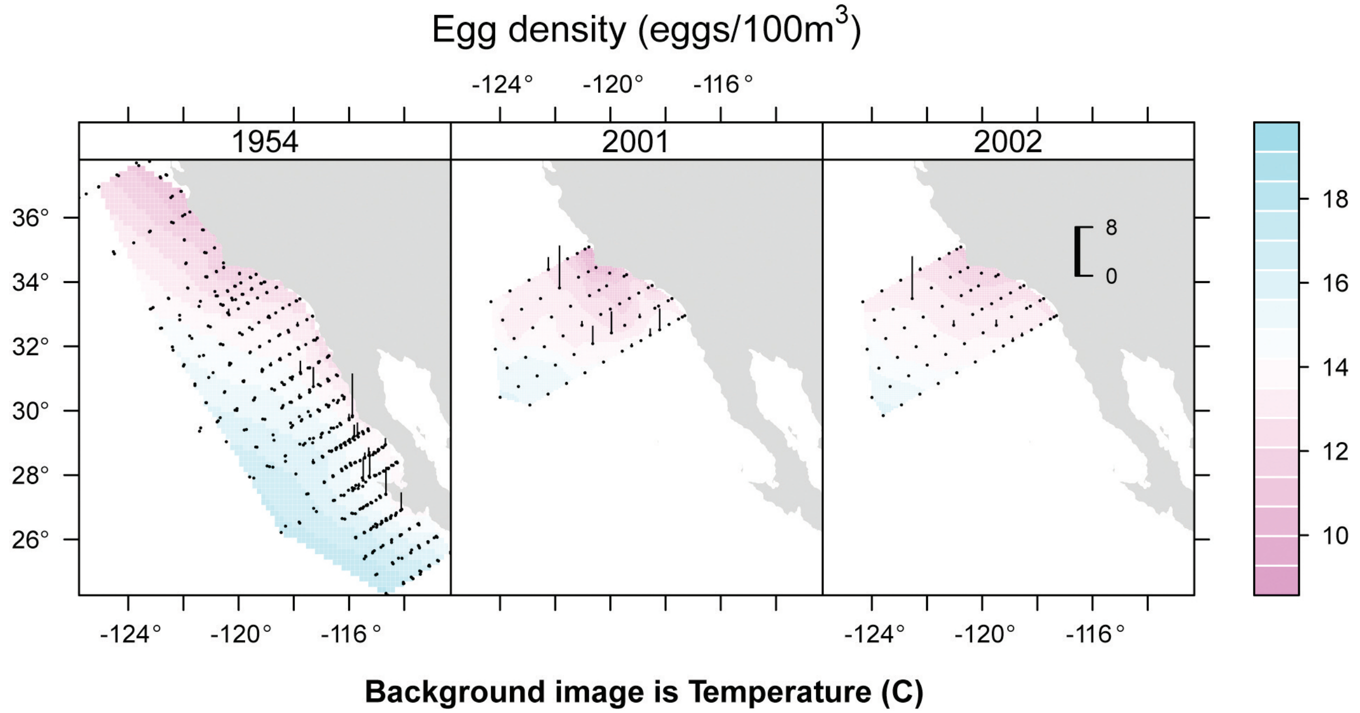

Figure 2. Density of sardine (*Sardinops sagax*) eggs (bars) sampled at CalCOFI stations in spring of 1954, 2001, and 2002 plotted over an interpolated surface of mean water temperature in the upper 50 m, as sampled at CalCOFI stations (color image). Black dots indicate sample locations. The plot was created using `splevelplot` as the base high-level plotting function. A custom panel function was used to over-plot points using `panel.spxyplot`, and bars using `panel.spstickplot`. The figure is based on an example data set named `calcofiDat` that is included in the package.

can be plotted in its native coordinate system as follows:

```
> spxyplot(mySpatialPoints)
```

We provide somewhat more complex examples to illustrate multiple features in a single graphic. These examples also demonstrate how custom panel functions can be used to combine graph types. Following the standard lattice convention, each high-level plotting function in **rcalcofi** has a default panel function that performs the actual plotting of symbols. For example, the default panel function for `spxyplot` is `panel.spxyplot`. More complex graphs can be created by replacing the default panel function with a custom panel function that combines several default types. Figure 2 illustrates the use of `splevelplot` as the base high-level plotting function. A custom panel function was used to over-plot points using `panel.spxyplot`, and bars using `panel.spstickplot`. The figure is based on an example data set called `calcofiDat` that is included in the package. The data describe CalCOFI samples collected during spring in 1954, 2001, and 2002. The color image depicts mean water temperature in the upper 50 m, as interpolated from data collected at each station using the `krig` option in `splevelplot`. Sample locations are indicated by black. Bars indicate densities of sardine eggs captured at each station.

Several other features of high-level plotting functions in **rcalcofi** are also illustrated in Figure 2. The shoreline polygons (technically a `gList` of polygons; cf., Murrell 2006) were passed to the function for plotting in each panel. The shoreline plotted was from the sample file named `shoreline` included with the package but could have been created using the `get.map` function. The figure was conditioned on years using the formula method (e.g., `temperature ~ coordinates | year`). For convenience, high-level functions in **rcalcofi** that accept a formula method can accept the word “coordinates” in place of the coordinate names (e.g., instead of `temperature ~ longitude * latitude | year`). The `splevelplot` function also calculated the correct aspect ratio and placed degree symbols on axis labels automatically. These could have been overridden by providing an `aspect` argument or a custom axis.

The figure was created from the `calcofiDat` data frame as follows. First, a year variable was added to the data frame based on the `datetime` column. Then, the data frame was converted to a `SpatialPoints DataFrame`.

```
> data(calcofiDat)
> ccdat <- calcofiDat
> ccdat$year <- substring
(ccdat$datetime, 1, 4)
> ccdat <- SpatialPointsDataFrame
(SpatialPoints(ccdat[c(“longitude”,
“latitude”)], proj4string = CRS
(“+proj=longlat”)), ccdat)
```

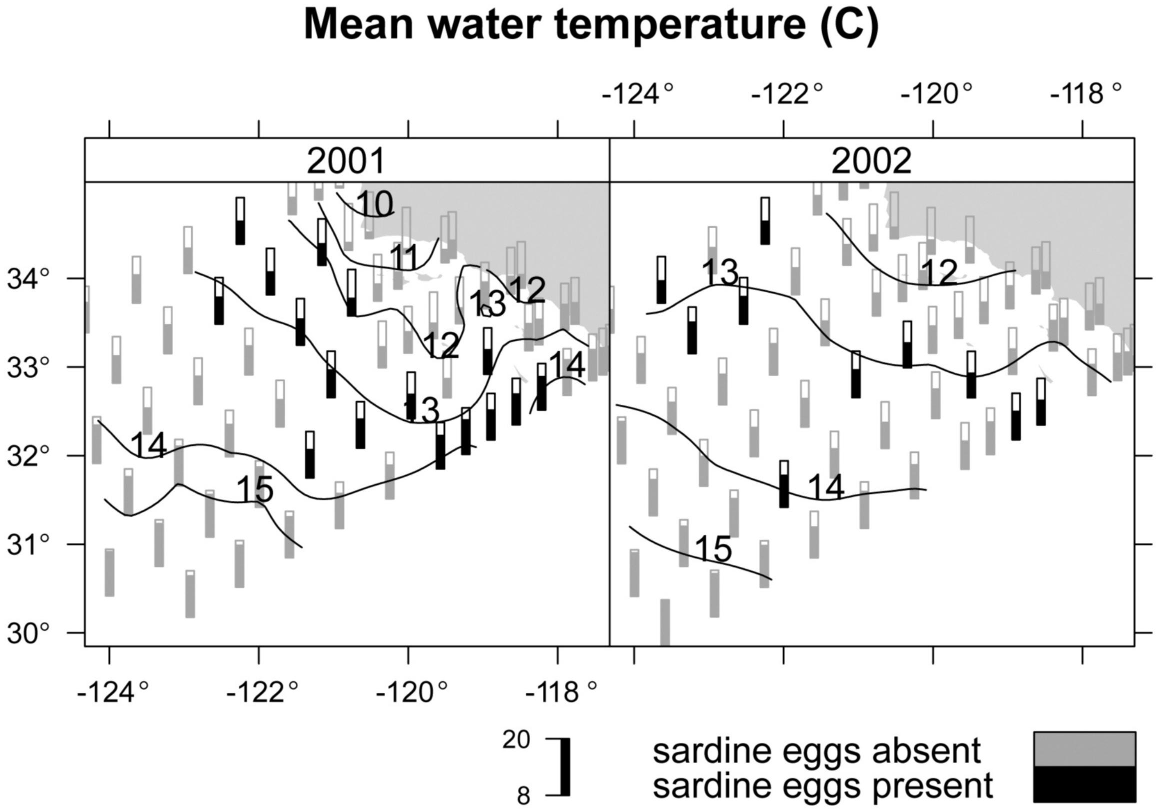

Figure 3. Mean water temperature in the upper 50 m, as measured at CalCOFI stations during spring 2001 and 2002. Data are plotted in two ways. First, filled bars indicate mean temperature at each station similarly to “thermometers” symbols in the standard **`symbols`** plotting function. An interpolated temperature surface is also over-plotted as a contour plot. The graph was created using **`spstickplot`** as the high-level plotting function with a custom panel function that called **`panel.spcontourplot`** to plot contours. A groups argument was used to plot stations where sardine eggs were present in black and stations where sardine eggs were absent in gray. Data are in the **`calcofiDat`** example data frame that is included in the package.

Then the plot was created as follows:

```
> splevelplot(temperature ~ coordinates
| year, ccdat, krig = TRUE, as.table =
TRUE, xlab = “”, ylab = “”, main =
expression(paste(‘Egg density
(eggs/100’, m^3, ‘)’, sep = ‘’)),
sub = ‘Background image is Temperature
(C)’, strip = strip.custom(bg =
“transparent”), layout = c(3, 1),
panel = function(...)
{
  panel.splevelplot(...)
  panel.map(map = shoreline,
proj4string = “+proj=longlat”)
  subscripts <- list(...)$subscripts
  panel.spxyplot(ccdat[subscripts, ],
proj4string = “+proj=longlat”, col =
“black”, pch = 20, cex = 0.1)
  panel.spstickplot(ccdat[subscripts,
“eggs”], proj4string = “+proj=longlat”,
filledBars = FALSE, col = “black”,
width = unit(0.01, “npc”))
  })
```

The key for the stickplot was added using the function **`spstickplotKey`**:

```
> spstickplotKey(width = unit(0.01,
“npc”), minval = min(ccdat$eggs,
na.rm = TRUE), maxval = max(ccdat$eggs,
na.rm = TRUE), col = ‘black’, border =
‘black’, vp = viewport(x = unit(0.8,
“npc”), y = unit(0.6, “npc”)),
draw = TRUE)
```

We used a subset of the same data, years 2001 and 2002, to plot mean water temperature in the upper 50 m (fig. 3). The data were plotted in two ways. The **`spstickplot`** function was used to indicate measurements at each station, with framed bars indicating the minimum and maximum values of bars. An interpolated surface of temperature was over-plotted as contours on each panel using **`panel.spcontourplot`**. The plot was conditioned on years, and grouped by the logical variable **`presence`** to indicate stations where sardine eggs were captured in black, and stations where no sardine eggs were captured in gray. The data were prepared and the basic graph was plotted using the following commands:

```
> ccdat2 <- ccdat[ccdat$year %in%
c('2001', '2002'), ]
> ccdat$presence <- ifelse(ccdat$eggs >
0, "present", "absent")
> spstickplot(temperature ~ coordinates
| year, ccdat2, as.table = TRUE,
groups = presence, xlab = "",
ylab = "", width = unit(0.015, "npc"),
col = c('darkgray', 'black'), border =
c('darkgray', 'black'), strip =
strip.custom(bg = "transparent"),
layout = c(2, 1), main = 'Mean water
temperature (C)',
panel = function(...)
{
  subscripts <- list(...)$subscripts
  panel.map(shoreline, '+proj=longlat')
  panel.spstickplot(...)
  panel.spcontourplot(ccdat2[subscripts,
'temperature'], krig = TRUE,
proj4string = '+proj=longlat',
cex = 0.5)
})
```

Two additional commands were used to generate the group key and the bar key:

```
> draw.key(list(text=list(lab =
c('sardine eggs absent', 'sardine eggs
present')), rect = list(col =
c('darkgray', 'black'))),
vp = viewport(x = unit(0.75, "npc"),
y = unit(0.22, "npc")), draw = TRUE)
> spstickplotKey(width = unit(0.015,
"npc"), minval = min(ccdat$temperature,
na.rm = TRUE), maxval =
max(ccdat$temperature, na.rm = TRUE),
col = 'black', border = 'black',
vp = viewport(x = unit(0.5, "npc"),
y = unit(0.22, "npc")), main = TRUE,
draw = TRUE)
```

Gridding Data in the CalCOFI Coordinate System

Gridding data can be accomplished using the overlay method exactly as described in the **`sp`** package. Basic gridding of data can be accomplished in **`rcalcofi`** even more conveniently using the **`pixelize.spatialdat`** function. This calls the **`overlay`** function to match spatial data to grid cells, and then creates a new grid with average values for the data in each grid cell (or another specified function such as the median). For example, a grid in the form of a **`SpatialPixels`** object from line 30 to line 120, with default cell sizes 3-1/3 lines by 10 stations, was created using the **`calcofi.grid`** function:

```
> ccgrd <- calcofi.grid(lineRange =
c(30, 120))
```

We overlayed the grid onto the example data set named **`TPH_ssta_8day_20060416`** that is included in the package. The data set consists of remotely-sensed sea surface temperature measured at 5.5 km resolution by the Pathfinder mission. The data are expressed in longitude and latitude for geographic range 28° to 42°N and -135° to -112°W for the eight-day period centered on 16 April 2006. These data were downloaded from the NOAA Coastwatch server using the **`get.dap.data`** function described below. The data were converted to a **`SpatialPointsDataFrame`** named **`llimagedat`** using the standard **`sp`** method:

```
> data(TPH_ssta_8day_20060416)
> llimagedat <- TPH_ssta_8day_20060416
> llimagedat <- SpatialPointsDataFrame
(cords = llimagedat[c("x", "y")], data
= llimagedat["z"],proj4string =
CRS("+proj=longlat"))
```

A new grid named **`ccimage`**, containing mean sea surface temperatures for each cell of the CalCOFI grid, was created using the **`pixelize.spatialdat`** function. The function handled the different projections of the two data sets automatically:

```
> ccimage <- pixelize.spatialdat
(llimagedat, ccgrd)
```

The gridded data are plotted in Figure 4. The plot was further customized before plotting with a different shoreline map. We created **`shoreline2`** using the **`get.map`** function. The map used a high-resolution gshhs shoreline file similar to the **`shoreline`** data, but light yellow as a fill color:

```
> gshhsPath <-
'/Users/eweber/calcofi/gshhs/gshhs_h.b'
> shoreline2 <- get.map(gshhsPath =
gshhsPath, col = 'lightyellow', border
= 'transparent', xlim = c(-136, -114),
ylim = c(22, 45))
```

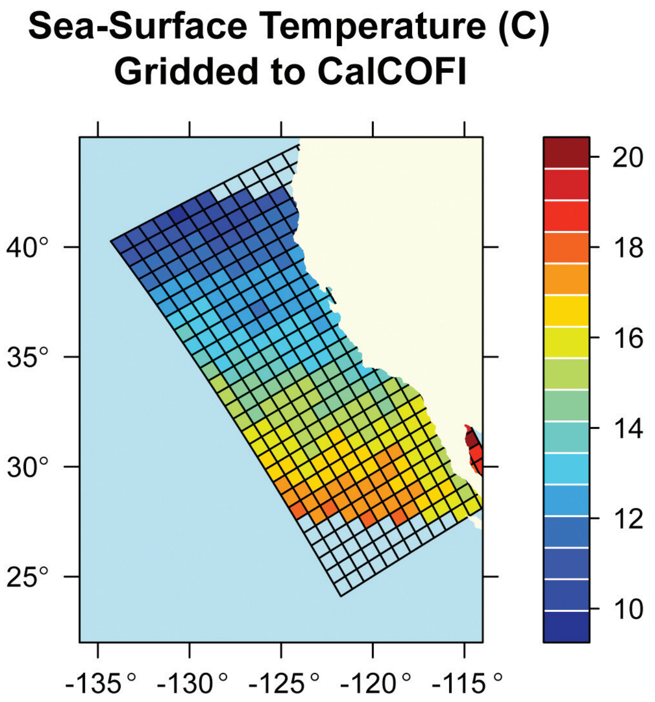

Figure 4. Mean sea surface temperature for the eight-day period centered on 16 April 2006. Original data were Pathfinder measurements expressed in longitude and latitude at 5.5 km resolution, and contained in the example data set named `TPH_ssta_8day_20060416`. The data were gridded to cell sizes of 3-1/3 lines by 10 stations in the CalCOFI coordinate system using the `pixelize.spatialdat` function. Data were plotted using the `spimageplot` function with a custom panel that included the `panel.spgridplot` function to create the black grid that is superimposed on the image.

The graph was plotted using the following commands:

```
> proj4string <- ‘+proj=longlat’
> trellis.par.set(axis.text = list
(cex = 0.9))
> splevelplot(ccimage, proj4string =
proj4string, xlim = c(-136, -114),
ylim = c(22, 45), proj4string.limits =
proj4string, xlab = ‘’, ylab = ‘’,
main = ‘Sea-Surface Temperature
(C)\nGridded to CalCOFI’, col.regions =
tim.colors(100),
panel = function(...)
{
  panel.fill(col = ‘lightblue’)
  panel.splevelplot(...)
  panel.spgridplot(ccimage,
proj4string)
  panel.map(shoreline2, proj4string)
})
```

Note that the grid was expressed in the CalCOFI coordinate system, but plotted in longitude and latitude by providing the `proj4string` argument `+proj=longlat`. The `panel.fill` function was used to create the light blue background behind the image and the shoreline. A different color palette for the image was also specified using the `col.regions` argument.

Downloading Remotely Sensed Data

The `rcalcofi` package includes functions to download freely available remotely sensed data from the NOAA Coastwatch server (http://coastwatch.pfel.noaa.gov/). The package includes a summary table of available sensors and data types called `dapDat.Rda`. The `get.dap.info` function can be used to print these data or construct a call to the `get.dap.data` function, which is used to download data. For example, the following code will download SEAWIFS monthly chlorophyll data for the given date and range, which is summarized as row 63 in `dapDat.Rda`:

```
> dapcall <- get.dap.info(63, c(28,
29), c(-135, -134), “2006-04-16”,
saveFile = FALSE)
> dapcall
> eval(dapcall)
```

The `get.dap.data` function can also be called directly:

```
> fileType <-“xyz”
> latRange <- c(28, 29)
> lonRange <- c(-135, -134)
> satellite <- “TPH”
> variable <- “ssta”
> dte <- “2006-04-16”
> timePeriod <- “8day”
> get.dap.data(satellite, variable,
timePeriod, dte, lonRange, latRange)
```

The function will automatically save the file in the default directory using a file name that indicates the sensor, date, and time period downloaded (e.g., the `TPH_ssta_8day_20060416` data frame was downloaded using this function), unless the `saveFile` argument is set to FALSE. The `check.dap.dates` function queries the NOAA Coastwatch servers to find available dates for data from a given sensor. It may be called manually, and is called automatically if a `get.dap.data` call fails. These functions are adapted (with permission) from the `xtractomatic` R program provided by Dave Foley and Cindy Bessey, NOAA Southwest Fisheries Science Center, Environmental Research Division, Pacific Grove, California. The `xtractomatic` program provides an alternative method of retrieving satellite data. It can be downloaded at http://coastwatch.pfel.noaa.gov/coastwatch/CWBrowserWW360.jsp?get.

Miscellaneous Functions

Several other simple miscellaneous functions that are included in `rcalcofi` are likely to be useful to other researchers working with CalCOFI data. The most frequently used of these are probably **`calculate.mld`**, **`calculate.distance.offshore`**, **`cols.to.zmatrix`**, and **`zmatrix.to.cols`**. The **`calculate.mld`** function returns an estimate of mixed-layer depth, given density, and water depth, following the procedure described by Kara et al. (2000). The **`calculate.distance.offshore`** function calculates the nearest distance from shore (as represented by a **`SpatialPolygons`** object) for each point in a matrix of locations. The **`cols.to.zmatrix`**, and **`zmatrix.to.cols`** functions convert spatial data between column (matrix or data frame) formats and the list format used by functions such as **`image`** and **`contour`**.

DISCUSSION

The **`rcalcofi`** package has reached a level of development where it may be useful to other researchers, despite relatively limited testing as part of our own research. We anticipate that additional refinement will be needed and welcome any bug reports as they are discovered. Although the package was developed with analysis of CalCOFI data in mind, much of the functionality is likely to be useful for other types of data. The spatial plotting functions may be particularly useful for other areas of fisheries and oceanographic research.

Some of the functionality of the package can be accomplished more computationally efficiently using GIS software or other programs. Although it is often convenient to conduct analyses using pure R solutions rather than working interactively between R and other programs, alternative approaches may be preferable when working with very large data sets. For such cases, the Spatial task view on the CRAN website provides an up-to-date list of applications that work well with R.

We consider **`rcalcofi`** to be primarily a package of convenience functions rather than one that introduces major new functionality. The authors of the core software and packages upon which **`rcalcofi`** relies have done most of the difficult programming. Users should not overlook existing functionality outside of the package when analyzing CalCOFI data. For example, standard graphics or standard **`lattice`** graphics may be as simple to use as our plotting functions in some cases when all data are in the same coordinate system.

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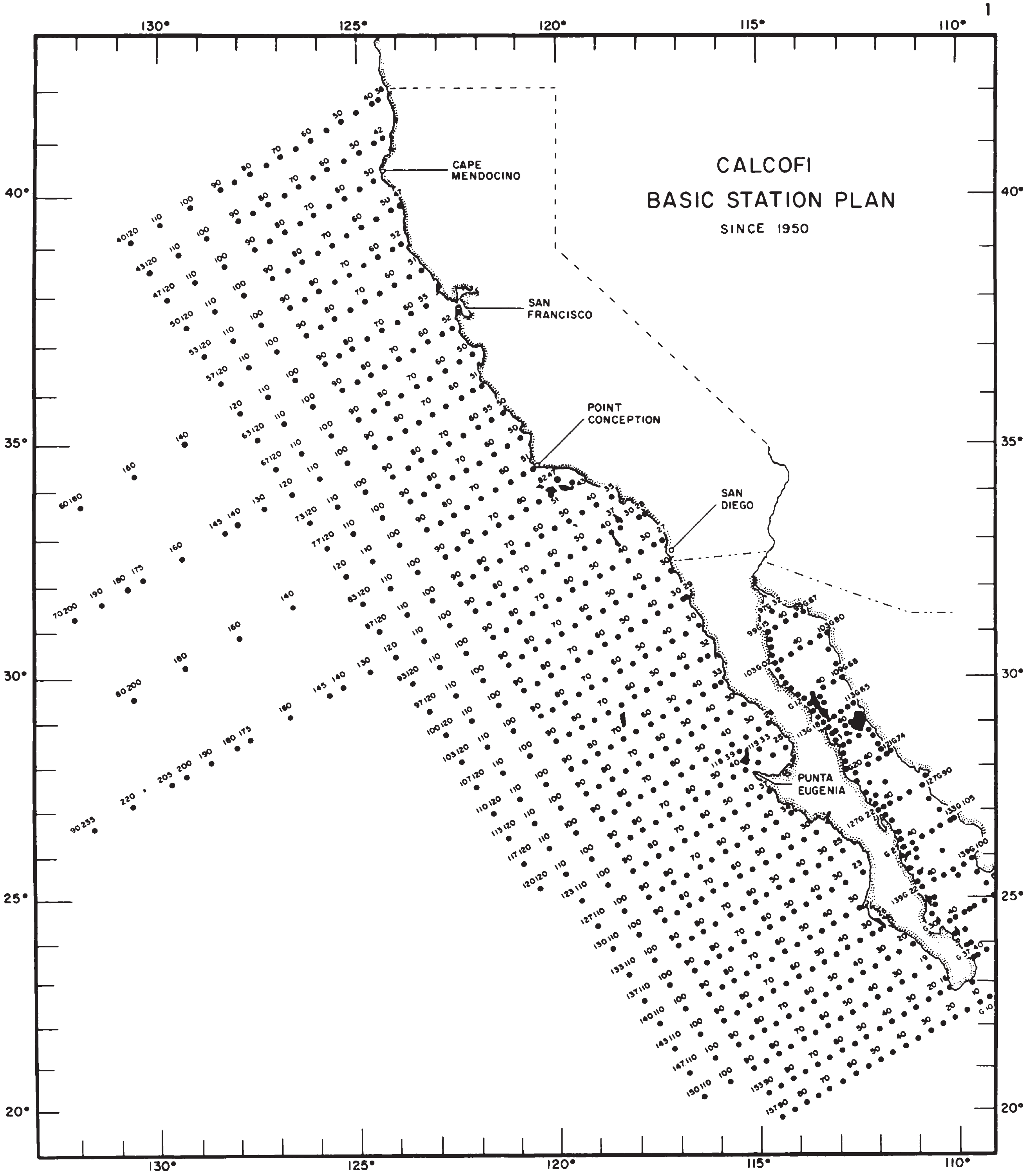

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