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CalCOFI in a Changing Ocean

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"The data and the samples are to be trusted, and they can be used with confidence…California, this nation, and the world are fortunate that those who began this program have continued it."

—John Knauss, former Under Secretary of Commerce for Oceans and Atmosphere

In 1999 the California Current changed. The ocean cooled, became somewhat less thermally stratified, and several characteristic species of zooplankton either decreased or increased in biomass. Many of these changes have persisted since that time (Figure 1). These ecosystem changes follow earlier shifts that occurred in 1976–77. Imagine the potential for misunderstanding the Northeast Pacific in the absence of such long-term observations. Any single year or limited group of years could yield a spurious picture of a dynamic ecosystem. Policy decisions and management guidelines would fail because they failed to take account of the underlying long-term variability.

The time series illustrated in Figure 1 are but a small window on the interdisciplinary ecosystem research for which the California Cooperative Oceanic Fisheries Investigations (CalCOFI) is known. CalCOFI comprises extensive physical and chemical oceanographic studies, detailed observations of phytoplankton and zooplankton, and comprehensive analyses of fish eggs and larvae. Built upon these core measurements is a suite of ancillary programs. These range from iron fertilization experiments to molecular genetics of zooplankton, from validation of bio-optical algorithms for satellite remote sensing to development of new underway free-fall probes, from assessment of marine mammals and birds to "control volume" budgets for ocean regions. Such ancillary programs capitalize on the extensive measurements and oceanographic context furnished by CalCOFI. CalCOFI is presently a consortium of three partners: the Southwest Fisheries Science Center of the National Marine Fisheries Service (NMFS)/National Oceanic and Atmospheric Administration, the California Department of Fish and Game (CDF&G), and Scripps Institution of Oceanography/University of California, San Diego (Scripps/UCSD).

In this article we examine how more than five decades of sustained (and ongoing) ocean observations came about, including the original motivation for such extensive measurements, well before today's imperative to understand long-term changes in ocean ecosystems. We also discuss a few of the major scientific contributions of CalCOFI and point to the directions in which the program is currently evolving.

Origins of CalCOFI

CalCOFI began as a response to the sardine crisis. During the 1920s and '30s more sardines (*Sardinops sagax*) were landed off the California coast than any other fish in North America. From 1922 to 1946, the catch of Pacific sardines (by weight) exceeded that of all other California fisheries combined and was the most lucrative finfish harvest (Marine Research Committee, 1953). The catch, however, plummeted from ca. 718,000 metric tons in 1936–37 to 118,000 metric tons in 1947–48 (Radovich, 1981). Fishers, processing plants, and canneries from Monterey's Cannery Row to the Los Angeles area suffered. In response, in 1947 the California legislature implemented a landing tax on commercial sardine, specifically earmarked to help identify causes of the sardine decline (Scheiber, 1990). In 1948, the Marine Research Committee (MRC), a joint committee of scientists and industry representatives, was formed to oversee administration of the funds. The MRC formed a technical committee composed of Harald U. Sverdrup of Scripps Institution of Oceanography, Oscar Sette of the U.S. Fish and Wildlife Service, Richard Croker of the California Fish and Game Commission scientific staff, and Robert Miller of the California Academy of Sciences. The Hopkins Marine Station of Stanford University also participated in early research. At Scripps, the Marine Life Research Program was initiated, later to become the Marine Life Research Group, now incorporated into the Integrative Oceanography Division.

Cruises to survey sardine eggs and larvae had been conducted in 1929–32 and 1937–41 (Smith, 1990), prior to the sardine collapse. But now, in response to the mandate of the MRC, truly remarkable new field efforts commenced. Following two preliminary cruises in early 1948, the systematic CalCOFI time series as

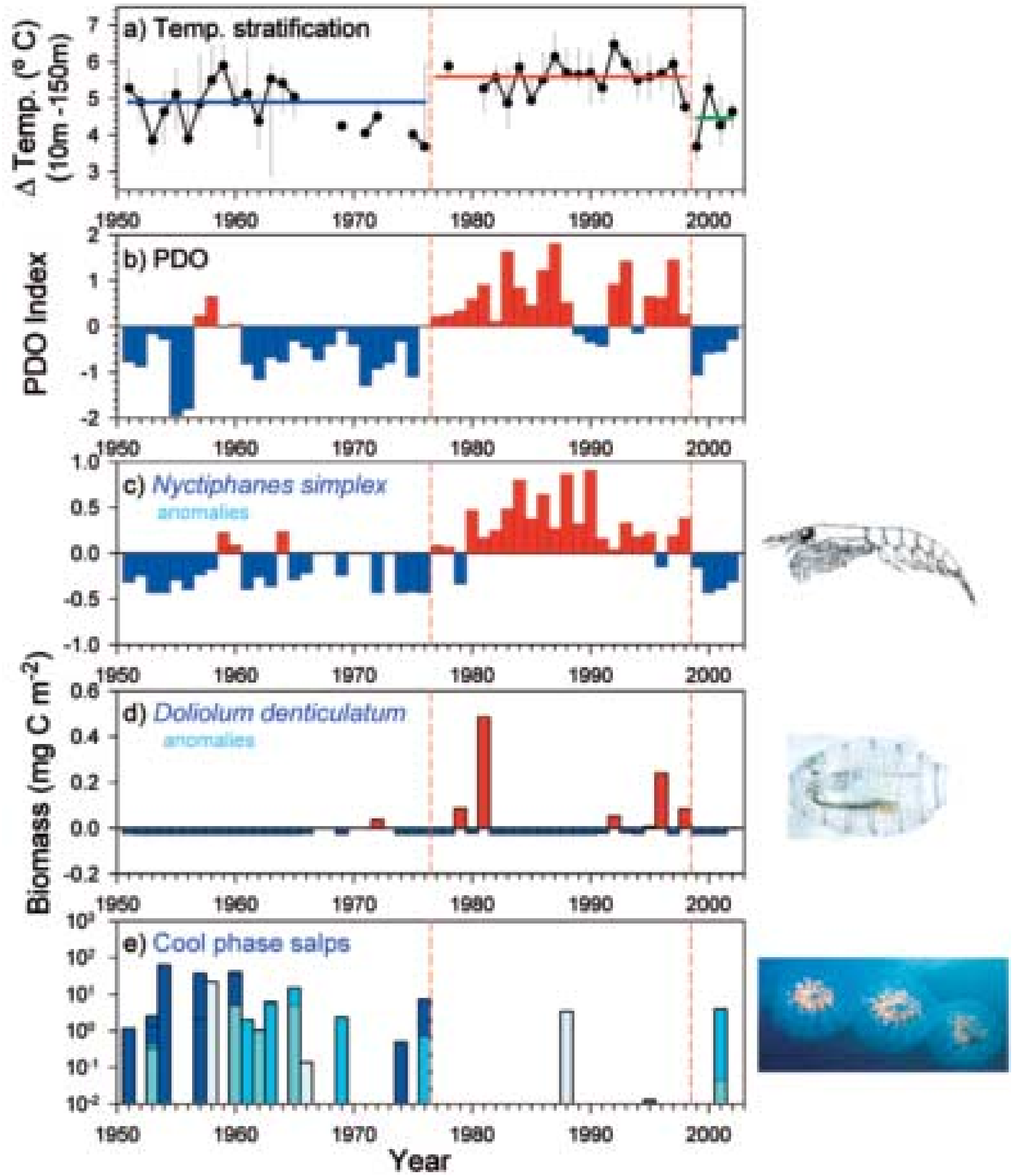

Figure 1. *Long-term variability in the Northeast Pacific ocean, between 1951–2002.**(a)** Springtime temperature stratification in the California Current, from CalCOFI, lines 80–93, offshore to station 70 (median ± 95% C.L.),* ***(b)*** *Annual averages of the Pacific Decadal Oscillation Index (Mantua et al., 1997),* ***(c)*** *Anomalies of springtime carbon biomass of the euphausiid* Nyctiphanes simplex, ***(d)*** *Anomalies of springtime carbon biomass of the doliolid* Doliolum denticulatum, *and* ***(e)*** *Springtime carbon biomass of one assemblage of salps. Dashed vertical lines indicate hypothesized nodal points for ecosystem shifts in the Northeast Pacific, a subject of active research. Panels a, b, d, and e are from Lavaniegos and Ohman (2003), and Panel d is derived from Brinton and Townsend (2003). Doliolid illustration courtesy of Mitchell Beazley (Bramwell, 1977) and the salp* Cyclosalpa affinis *reprinted with permission* (*Wrobel and Wills, 1998).*

we know it today began with a three-ship cruise in March 1949. Scripps's Roger Revelle had a critical role in securing and outfitting research vessels for this purpose (Scheiber, 1990). At the time CalCOFI was launched, sampling extended from the Canadian border to the tip of the Baja California peninsula. Three ships plied most of these waters monthly throughout the 1950s, resulting in a field program of astonishing scope. Today, the geographic area occupied has decreased to a smaller subset of the region within the U.S. Exclusive Economic Zone, and is sampled quarterly. The program was initially called the California Cooperative Sardine Research Program, reflecting its original focus, but in June 1953 the present name was adopted, as the program expanded to include work on other fishes sometimes referred to as "substitute sardines" (northern anchovy, jack mackerel, and Pacific mackerel). The landing tax was expanded to include these species in 1952–53. Although the MRC was dissolved by the California legislature in 1978, CalCOFI continued as a cooperative research unit by mutual agreement of the NMFS, CDF&G, and UC.

Scientific Results: Selected Highlights

In spite of primitive equipment, the early years of CalCOFI revealed unexpected details and the flow field was revealed to be increasingly "more complicated and peculiar" than expected, remarked Scripps Professor Emeritus Joe Reid. Nevertheless, at the end of eight years, there was little indication of large interannual variation. "*It had been eight soggy years, frustrating to contemplate*," Reid said. That was about to change.

On the regional scale, physical, chemical and biological observations "*were interesting and informative in themselves. But they seemed to suggest relations between these fields that could be examined more effectively if data could be collected over a larger area*," Reid said. There was enough interest and enough resources to carry out—at least once—a complete coverage of much of the Pacific Ocean. In the summer of 1955, Reid coordinated a huge effort by numerous institutions from the United States, Canada, and Japan to provide near-synoptic coverage of most of the North Pacific Ocean. The NORPAC Expedition provided the framework for much of what scientists now know about large-scale spatial distributions in the Pacific, and altered the way scientists interpreted change in the California Current. Reid's classic 1962 paper showed the relationship between nutrients (especially those at 100 m) and zooplankton displacement volume in the upper few hundred meters, as well as the major circulation features.

We recognize a need to simultaneously develop new perspectives and measurement methods, yet retain continuity with the existing time series.

Fueled by material from CalCOFI and NORPAC, studies by Martin A. Johnson and his students (including Leo Berner, Bob Bieri, Thomas Bowman, Ed Brinton, and John McGowan) revealed that distributions of single plankton species are also closely related to surface circulation and to Sverdrup's water mass boundaries. In February 1957, when this idea was in its infancy, it was explored in a series of nonsensical (but somewhat prophetic) memos. The first, from John Knauss to Brinton refers to Ed's "talk at staff luncheon on the possibilities of euphausiids as water mass indicators." Knauss realized that this idea lends itself to exploitation…

> *Now, one of the many problems facing the Navy is that there is not much point in building a submarine like the Nautilus that can stay under water for weeks at a time if it has to come up for morning and evening stars to find out where it is…Listening to your talk I got the idea that indicator species offer a real possibility for the solution of this difficult and important problem."*

Two days later came a reply to Knauss from Roger Revelle, in which Revelle points out the necessity to consider possible counter measures: "*For example, jamming the Kuroshio with euphausiids from the Oyashio, and vice versa*."

Before this plan was fully developed, additional contributions were offered by Brinton, Johnson, Walter Munk, and the American Miscellaneous Society. It seems, however, that their efforts were never properly appreciated by the U.S. Navy.

The correspondence between species distributions and water mass characteristics was quantified by Fager and McGowan (1963). Their paper expanded the focus of plankton ecology from single species to associations of species, and from regional to basin-wide scales.

In 1957, unusual weather conditions broke loose in the North Pacific. In Alaskan harbors, ice melted at the earliest time on record. Hawaii recorded its first major typhoon. The seabird-killing El Niño visited the Peruvian coast. In the California Current, ocean temperatures increased and the prevailing north winds slackened. Sport fishermen landed 2,805 mahi mahi against a previous high of 15, and windrows of southern "tuna crabs" piled up on beaches as far north as Monterey, California.

CalCOFI now had eight years of data from the California Current against which to judge the '57–'58 event. Because the anomalies were so large and were echoed in disparate locations throughout the Pacific, the 1958 CalCOFI conference at Rancho Santa Fe, California, was dedicated to "The Changing Pacific Ocean in 1957 and 1958" (Sette and Isaacs, 1960). Biologists, oceanographers, meteorologists, and even an astrophysicist were invited to examine these anomalies from their own perspectives. During the conference, it became apparent that events in Alaska and Peru and the California Current were part of a common pattern that was at least Pacific-wide. Participants marveled at the possibility that large-scale anomalies reverberate between ocean and atmosphere and may be transmitted globally. (Scripps research meteorologist Jerome Namais said, "*Altho I am not ready to propose anything deserving the designation of theory, I believe that there are interactions between the North Pacific anticyclone on the one hand and its Southern Hemisphere counterpart*.") The concept of the North Pacific as a world weather factory was born, and as Reid (1988), recollects "*neither* *oceanography nor long-range weather prediction has ever been the same.*"

Curiously, although the tropical phenomenon known as El Niño was discussed at the conference, and analogies were drawn, the specific connection between El Niño and the rest of the Pacific was not made. Indeed, it was nearly 20 years before the CalCOFI data set was sufficiently long that two graduate students, Dudley Chelton in physical oceanography and Patricio Bernal in biological oceanography, could statistically relate El Niño events at the equator with observed changes in the California Current (previously these had been hypothesized as a consequence of theoretical considerations). Compelling evidence was produced that advection dominates upwelling over a large portion of the California Current system. Chelton's study also suggested an inverse relationship between sea level in the subarctic Pacific and the California Current, a current focus of the U.S. GLOBEC Northeast Pacific program.

This work opened our eyes to the magnitude and scale of change in the ocean—and to the ecological implications of climate–ocean interactions.

If the El Niño phenomenon was a surprise, so was the next major climatic event—the climate shift of the mid-1970s. The first indication of the mid-1970s climate change came not from the California Current, which is too variable for early detection of changes, but in the more docile central North Pacific gyre. In 1968, several CalCOFI researchers had begun a multiyear study of the central Pacific ecosystem. Their purpose was to understand the structure of the pelagic community in a relatively stable environment, where biological interactions were expected to be a dominant force in community regulation; the hope was that such information would help untangle the biological and physical factors regulating the complicated species patterns in the California Current System. After 18 years, it became obvious that something odd had happened in the mid-1970s: the chlorophyll concentration deep in the water column (but not at the surface) had nearly doubled (Venrick et al., 1987). While a link with climate was postulated, the huge scale of the interdecadal climate shift was not recognized for several years. It was 10 more years before CalCOFI had a data set that was sufficiently long (45 years) to identify the magnitude and nature of this climate change in the California Current System. By 1995 it was evident that sea level had risen, the upper strata of the ocean had warmed, and macrozooplankton biomass had declined by a remarkable 70 percent relative to 1951–57 (Roemmich and McGowan, 1995a; Roemmich and McGowan, 1995b).

However, total zooplankton biomass does not tell the entire story. Current research delving deeply into the exceptional archive of CalCOFI plankton samples, which are housed in the Scripps Pelagic Invertebrates Collection, is yielding a new view of the response of zooplankton communities to climate forcing. During the warm phase of the Pacific Decadal Oscillation, which corresponds to the time period of decline of total biomass, the biomass of some species of macrozooplankton, such as the subtropical euphausiid *Nyctiphanes simplex* and the doliolid *Doliolum denticulatum*, actually increased (Figure 1; Brinton and Townsend, 2003; Lavaniegos and Ohman, 2003). Such changes suggest that the ecosystem shifts are associated with altered ocean circulation, and not merely changes within the resident plankton assemblage. At the same time, many species of salps declined (Figure 1), as did total numbers of seabirds (Veit et al., 1996), with changes in abundance of many species of fish larvae (Moser et al., 2001). There has been no long-term decline in abundance of dominant copepod species over the last half century, and their relative composition has been stable. With the 1976–77 climate change, about a quarter of the sub-dominant copepod species showed a change in abundance (Rebstock, 2001; Rebstock 2002). Thus, we now see that pelagic communities can be restructured by such climate perturbations.

At present, there is active debate whether yet another climate shift may have occurred in 1998–99 (see Figure 1), providing us with an unequalled opportunity to direct research into the mechanisms by which these large-scale climate shifts influence the California Current System and are transmitted through the ecosystem. New challenges have been made to some of the analytical methods used to detect "regime-shifts," such as the 1976–77 transition (e.g., Davis and Rudnick, 2003). While we are focused on this marvelous, new scale of change, we cannot but help wonder from where and when the next big ocean–climate surprise will come.

Space does not permit us to do justice to the substantial body of CalCOFI research, or the related ancillary programs, so here we have highlighted just a few of the major contributions from Scripps investigators. The scientific legacy of our partners in the CalCOFI consortium are equally rich. The contributions of our colleagues at the SWFSC/NMFS on the early life history of marine fishes, and the relationship of early-life history phases to variations in adult stocks, are legendary and have influenced scientists' thinking throughout the world. A few entry points to the scientific literature are provided in Table 1.

Dissemination of Scientific Results

CalCOFI data are disseminated widely to the scientific community and to public agencies (see Table 2). CalCOFI data are deposited in the National Oceanographic Data Center archives and, in fact, some people use CalCOFI data without their own knowledge. Approximately one-third of the data used for development of the NASA Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project's algorithms have been developed with bio-optical information collected on CalCOFI surveys (Kahru and Mitchell, 1999; O'Reilly et al., 1998). A number of ocean and climate modeling

Table 1.

Selected Scientific Contributions of CalCOFI

- Multidecadal shifts in North Pacific pelagic ecosystems (Brinton and Townsend, 2003; Lavaniegos and Ohman, 2003)
- Fishery-independent estimates of historical population variability, reconstructed from collection specimens (e.g., Butler et al., 2003)
- Calibration of bio-optical algorithms for remote sensing of oceanic phytoplankton (O'Reilly et al., 1998; Kahru and Mitchell, 1999)
- Continuous underway fish egg sampling (Checkley et al., 1997)
- Landmark treatise describing the morphology, life history, and time series of geographic distribution of 500 species of marine fish eggs and larvae (Moser, 1996)
- Interdecadal warming of the California Current, increase in sea level, and concurrent decline in zooplankton biomass (Roemmich, 1992; Roemmich and McGowan, 1995a; Roemmich and McGowan, 1995b)
- Basin theory for population expansion of pelagic fishes (MacCall, 1990)
- El Niño impacts on marine invertebrates and fishes (Chelton et al., 1982; Butler, 1989; Rebstock, 2001)
- Speciation mechanisms in oceanic plankton (Fleminger, 1975; Goetze, 2003)
- Daily egg production method for estimating spawning stock biomass of epipelagic fishes (Lasker, 1985)
- Ontogeny of patchiness in pelagic fishes (Hunter and Coyne, 1982)
- Feeding ecology of larval anchovy (Hunter, 1981)
- Methodology for quantitative sampling of ichthyoplankton (Smith and Richardson, 1977; Smith et al., 1985)
- Stable ocean hypothesis (Lasker, 1975)
- Cyclical, historical variations in abundance of sardines and anchovies, from fish scales deposited in varved sediments (Soutar and Isaacs, 1974; Baumgartner et al., 1992)
- Correspondence between biogeographic distributions of planktonic organisms and large-scale ocean circulation (CalCOFI Atlas Series; Brinton, 1962; Reid et al., 1978)
- Objective definition of recurrent assemblages of plankton (Fager and McGowan, 1963)
- Relationship between nutrient distributions and zooplankton biomass on the scale of the Pacific basin (Reid, 1962)
- Circulation of the California Current System (Reid et al., 1958; Lynn and Simpson, 1987)
- Large-scale teleconnections in the atmosphere/ocean system (1958 CalCOFI Conference; Sette and Isaacs, 1960)

(Topics are listed in reverse chronological sequence.)

groups utilize CalCOFI data to initialize or test their models. Continuous underway fish egg sampling (Checkley et al., 1997) provides high-resolution spatial assessments of fish-spawning habitats (Figure 2) for use by a number of government and private-sector agencies. Additionally, the CalCOFI zooplankton/ichthyoplankton surveys (Figure 3) continue to provide the basis for fishery-independent assessments of a broad spectrum of marine organisms.

Future Directions for CalCOFI

CalCOFI's future looked bleak in the summer of 2002 when a $38 billion shortfall in the California budget caused the state to impose stringent budget cuts. The University of California elected to absorb much of its cut by decreasing allocations for research, resulting in total cessation of university support for CalCOFI operations (approximately 50 percent of the costs of the cooperative field program). Fortunately,

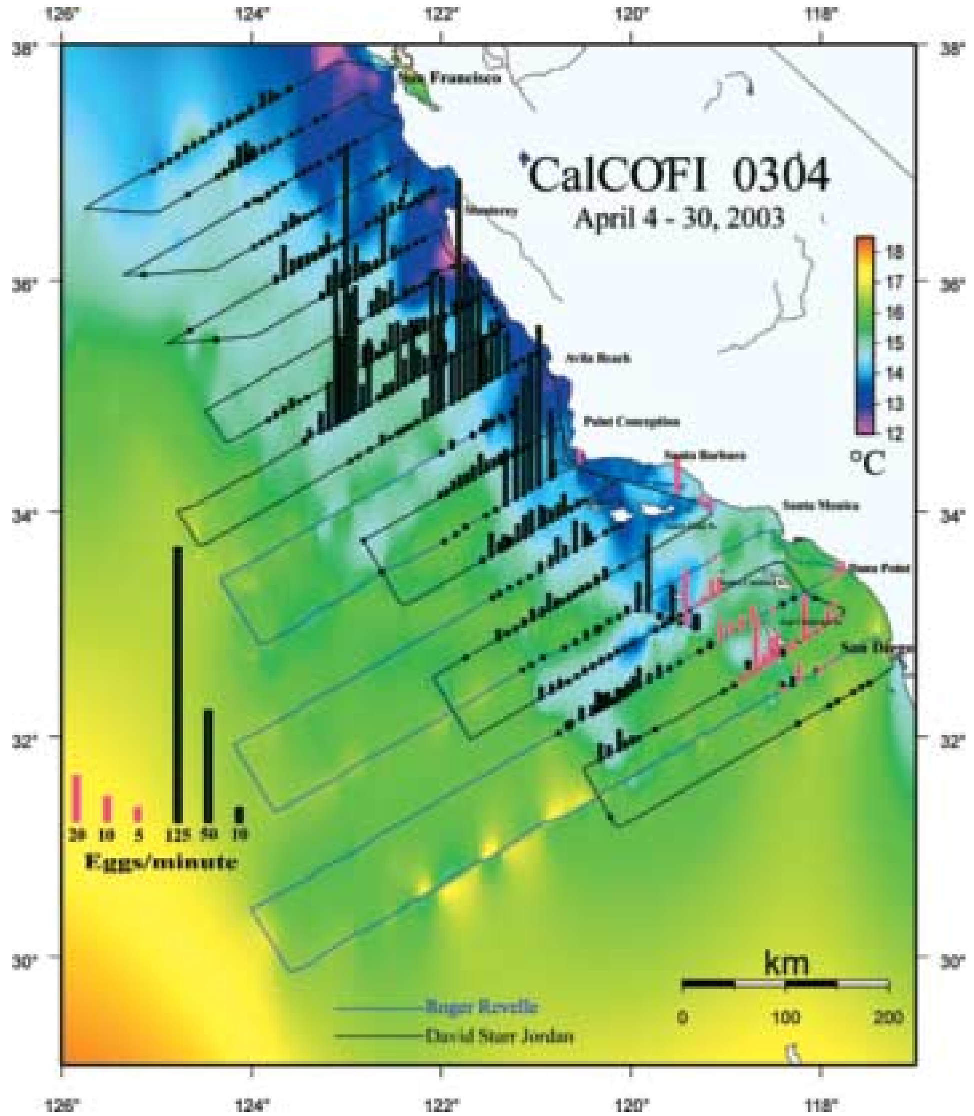

Figure 2. *Abundance of sardine eggs (*Sardinops sagax*, black bars) and northern anchovy eggs (*Engraulis mordax*, red bars with a different vertical scale) collected near the surface from CalCOFI cruise 0304 (April 2003), together with surface temperature (°C) from the underway CTD sensor. Note the spatial separation of sardine and anchovy eggs. Sardine eggs tend to be associated with the onshore-offshore temperature front and anchovy eggs are found in the warmer nearshore waters. Eggs were collected with the continuous underway fish egg sampler, CUFES (Checkley et al., 1997). Abundances are preliminary counts based on shipboard analyses and are subject to revision. Figure courtesy of D. Griffith and R. Charter, SWFSC/NMFS.*

the Pacific Coastal Observing System (PaCOS) concept (see the following paragraphs) has been received favorably and planning is moving forward with the support of NOAA. In the interim, CalCOFI has received emergency funds from both the Office of Naval Research and NOAA and operations are secure at least until summer 2004.

Despite this uncertain future, CalCOFI is looking ahead to the next half century. We recognize a need to simultaneously develop new perspectives and measurement methods, yet retain continuity with the existing time series. Some of the new directions being pursued are discussed next.

PaCOS

To expand the geographic scale of measurement in the California Current and enhance the capability to understand large-scale changes in pelagic ecosystems, an alliance is being built between CalCOFI and related measurement programs from Baja California, Mexico (the IMECOCAL program) to Vancouver Island, Canada. A linked network of ecosystem observational

Figure 3. *Sampling the California Current on a CalCOFI cruise. Photograph courtesy of S.L. Cummings.*

Table 2.
Communication of CalCOFI Results

- Major CalCOFI web sites:
  www.calcofi.org
  swfsc.nmfs.noaa.gov/FRD/CalCOFI/CC1.htm
  collections.ucsd.edu/pi/index.cfm
  swfsc.nmfs.noaa.gov/FRD/acceo/acceo1.htm
- 35 volumes of *CalCOFI Atlas,* summarizing circulation of the California Current and the distributions of hundreds of species of pelagic marine invertebrates and ca. 500 species of fish eggs and larvae.
- The journal *CalCOFI Reports,* fully peer-reviewed and in its forty-third year of publication; available electronically.
- Hundreds of papers in other scientific journals (tabulated in each annual issue of *CalCOFI Reports*)
- Data reports—SIO References Series, containing station data from each CalCOFI cruise; available electronically and in print form.
- National Oceanographic Data Center archives—CalCOFI data form the backbone of the Northeast Pacific data set in the NODC, which is managed by NOAA.
- Annual CalCOFI conferences, open conferences concerning the Northeast Pacific, held in Oct.–Nov. of each year.

programs will make it possible to resolve large-scale forcing in the Pacific and assess the spatial coherence of climate signals and ecosystem response in the entire California Current system.

Augmented Space/Time Resolution

New instrumentation is currently under development that will greatly enhance the spatial and/or temporal resolution of sampling, including gliders, autonomous zooplankton drifters, underway free fall conductivity, temperature, depth sensors (CTDs), moored sensors, and others.

Bridging the Offshore to the Nearshore Ocean

CalCOFI's oceanic sampling would be well complemented by a concerted scientific effort focusing on processes affecting the immediate nearshore environment, including the zone in which larvae of many benthic invertebrates are found and anthropogenic effects are often pronounced. Collaboration with colleagues around the margin of the Southern California Bight has begun.

Enhanced Coverage of Food Webs

New methods should permit assessment of additional elements of pelagic food webs that have not historically been addressed by CalCOFI. These include automated screening of plankton populations using molecular probes, imaging flow cytometer (FlowCAM) assessments of microplankton populations, instantaneous measurements of phytoplankton physiological state, and automated pattern recognition of pelagic organisms.

Coupled Biophysical Models

The long-term observational program of CalCOFI would be enhanced if it were more intensively merged with assimilative models for forecasting ecosystem impacts of El Niño, life history closure in marine organisms, control volume calculations, and other coupled bio-physical modeling, another future pursuit for the CalCOFI group.

Conclusion

In his review of CalCOFI's history and contributions, historian Harry N. Scheiber (1990) has called attention to two singular features of the program's legacy in addition to its extensive scientific insights and vital role in the management of marine resources. First, the collaborative nature of the program. At the outset CalCOFI included a state agency and a federal agency, two academic research laboratories, an academy of sciences, and members of the fishing industry. Despite different objectives, organizational structures, and scientific cultures (as well as turnover of people), the partnership of the three core participating groups has functioned effectively for more than five decades. It is a successful model for the types of collaboration needed to address other environmental concerns. Second, CalCOFI championed the ecosystem approach to fisheries research, one of the "glittering achievements" of the program (Scheiber, 1990). From its inception, the physical, chemical, and biotic environment of the fish populations of interest have been an integral part of the program. Integrative studies of ocean circulation, ocean–atmosphere interactions, plankton distributions, rate processes, and predator–prey interactions

Student Erica Goetze holds a cross-section of marine life from the Pacific Ocean.

have been key elements of the CalCOFI approach, and are now in wide use around the world.

What about the original question that spawned CalCOFI? It appears now that the crash of the sardine fishery occurred as the result of the unfortunate convergence of at least two factors: the development of excess fishing capabilities together with a natural, cyclical phenomenon of population decline. The coincidence of these processes had catastrophic effects on the sardine population and sardine fishery. We now know that sardine populations in widely disparate regions of the Pacific can vary concordantly on multidecadal time scales (Lluch-Belda et al., 1989; McFarlane et al., 2002). Thus the lessons learned by CalCOFI's studies are applicable to many sectors of the world ocean and to many other marine organisms. The greatest lesson of all may be that without the long-term perspective furnished by CalCOFI and related programs, we risk repeating the same mistakes.

Acknowledgments

We express appreciation to the pioneering scientists and leaders who initiated the CalCOFI program, as well as to the legions of seagoing personnel who have plied the waters of the California Current over so many years, maintaining the rigorous standards of CalCOFI measurements. We also express thanks to Scripps Director Charles F. Kennel and Scripps Director of Government Relations Kathleen B. Ritzman for their ongoing efforts on behalf of CalCOFI, to David Griffith and Rich Charter for providing Figure 2, to Sherry Cummings for Figure 3 and to David Field for assistance with calculations. This manuscript is contribution number 402 of the U.S. GLOBEC research program, which is supported by the National Science Foundation and by NOAA.

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