LONG-TERM MARINE ECOSYSTEM OBSERVATIONS TO SUPPORT SUSTAINABILITY & RESILIENCE IN THE CALIFORNIA CURRENT SYSTEM

California Cooperative Oceanic Fisheries Investigations (CalCOFI)

REVIEW 2017 - 2021

CalCOFI

Celebrating 72 Years

1949 - 2021

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CalCOFI
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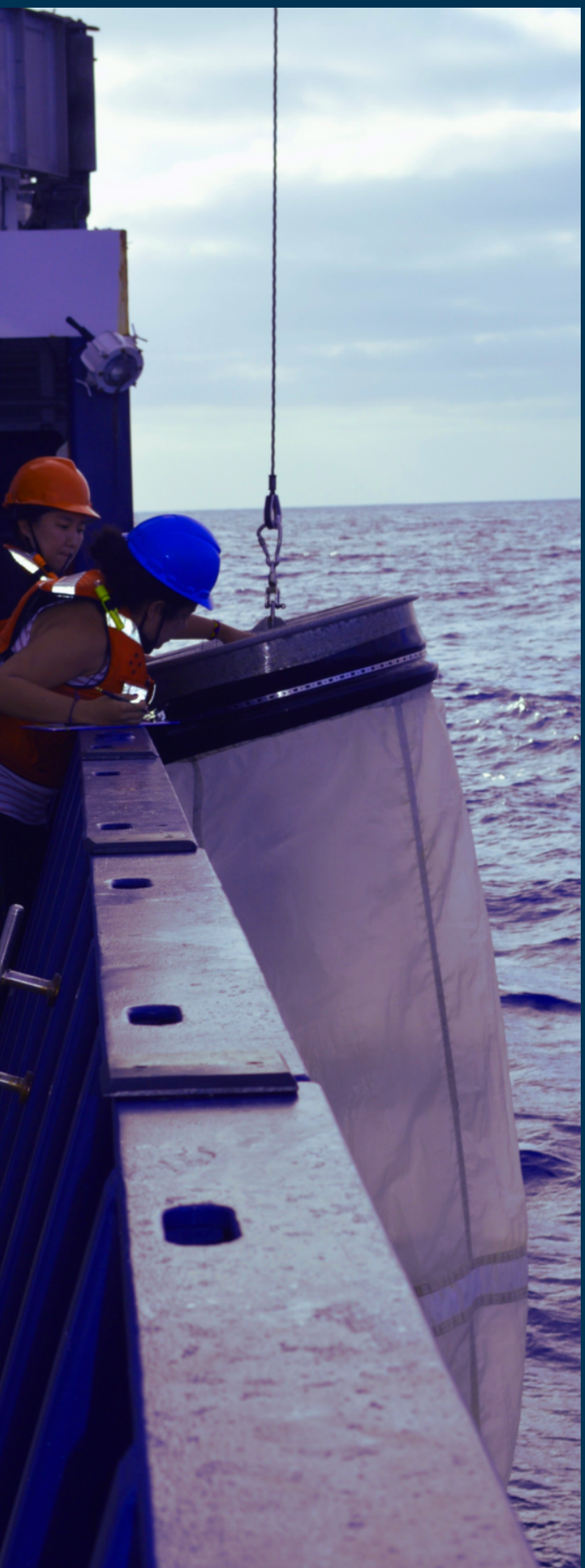
PURPOSE

This report reviews the progress, achievements, and goals of the CalCOFI program from the past 4 years (2017–2021). The report summarizes the background, vision, mission, goals, and initiatives of the CalCOFI program. We also showcase the future vision of CalCOFI including the challenges and opportunities in achieving CalCOFI's mission, and describe what we are going to collectively be working on moving forward. We plan to use the feedback from the review to refine our strategic plan and continue to develop and convene the CalCOFI Advisory Board.



EXECUTIVE SUMMARY

Human activities and changes in climate are affecting ocean ecosystems and human well-being. Managing these complex social-ecological systems requires an adaptive, holistic, integrated approach rooted in robust science and evidence-based decision making. Such an approach to research and management within complex systems relies on ongoing long-term monitoring, assessment, research, data synthesis, communication, and education that helps to better understand and refine future management decisions through an iterative process that also serves to train the next generation of ocean leaders.

The California Cooperative Oceanic Fisheries Investigations (CalCOFI) is a marine ecosystem research program off the coast of California that studies the physics, biogeochemistry, and biology of the marine environment. CalCOFI is one of the world's longest-running, integrated ocean ecosystem sampling programs that simultaneously collects biological, chemical, and physical observations and specimens across the California Current System (CCS) to inform research and management. While originally focused on questions related to sustainable fisheries, CalCOFI observations also inform questions related to integrated ocean management, renewable energy, offshore aquaculture, tourism, as well as marine spatial planning, all in the context of climate change. Specifically, CalCOFI data are used to understand population dynamics for a variety of commercially-important marine species as well as marine ecosystem processes in the California Current System. In addition, the CalCOFI community is a diverse network of stakeholders within various local, state, federal, and international organizations, who come together to share information, exchange ideas, and develop priorities for long-term monitoring in support of ecosystem and marine resource management and resilience in the California Current System.

HISTORY

Collaboration to understand rapidly changing marine ecosystems. CalCOFI began in the late 1940s in response to the collapse of the economically important sardine (*Sardinops sagax*) fishery on the US West Coast (Hewitt 1988). Competing hypotheses argued for overfishing versus environmental change as the dominant driver responsible for the sardine decline, and CalCOFI was founded to investigate the relationship between oceanographic conditions and sardine abundance. From the beginning, CalCOFI represented a unique partnership between academic, federal, and state partners, which now consists of the Scripps Institution of Oceanography (SIO) at University of California San Diego (UCSD), federal scientists at NOAA's National Marine Fisheries Service (NMFS), and scientists working for the California Department of Fish and Wildlife (CDFW). Collaboration and partnership have been at the core of the CalCOFI program since its inception.

CalCOFI as an ecosystem observing program. Although CalCOFI was initiated to investigate the disappearance of the California sardine and develop the means to optimally manage that fishery, CalCOFI has since evolved into the foremost interdisciplinary biophysical and fisheries oceanography observation program in the United States and, arguably, the world. CalCOFI's founders had the vision to create an ecosystem monitoring program at a time when ecosystem research was in its infancy, thus beginning an ecosystem observing program with unparalleled temporal coverage of a broad suite of biological and environmental observations. The foundational holistic, integrated thinking that gave rise to the CalCOFI program has served as an exemplary program for many other observing programs globally and has helped to shape marine ecosystem-based management.

Adaptation to ensure sustainability. Today, CalCOFI's focus has broadened to encompass the ecosystem of the southern California Current System, while adapting to capitalize on state-of-the-art observing methods (e.g., genomics). Because of the length of the time series, the program is invaluable for understanding the effects of long-term change on the marine ecosystems and the human communities that depend on them within the California Current System, the North Pacific, and internationally.

VISION

We envision a future of resilient, thriving coastal and marine ecosystems, human communities, and vibrant economies that prosper in tandem with a healthy ocean.

MISSION

CalCOFI is focused on collecting long-term ocean observations in support of research and management applications, diverse engagement, and education. We work to collect long-term integrated data to understand, predict, communicate, and design solutions that address the impacts of climate and long-term environmental change on marine ecosystems, living marine resources, and coastal communities in the California Current System.

GOALS

Observe Observe the ocean to support research and management

Engage Engage diverse stakeholders and communities

Educate Educate the next generation of ocean leaders and citizens

Observe

Generate ocean observations to support research and management

OVERVIEW

CalCOFI studies the physics, chemistry, and biology of the ocean and is the longest continuous marine ecosystem monitoring program globally.

In a modern context, CalCOFI conducts quarterly cruises (duration 2-4 weeks) from San Diego to north of San Francisco Bay and extends from the coast out to 360 nautical miles (667 km) offshore, spanning state, national, and international waters (Figure 1). Sampling is conducted aboard a variety of research vessels (CalCOFI ships) and core sampling is carried out by crew from the Southwest Fisheries Science Center (NOAA) and SIO and in most cases with support from collaborative program personnel (see Collaborative Programs) and volunteers, including early career professionals (see Educate).

CalCOFI provides information on the California Current System to generate and support research and inform the sustainable management of marine ecosystems in the context of climate variability and change.

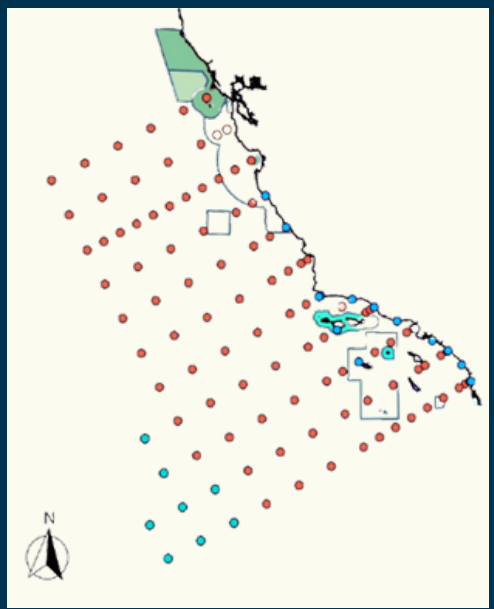
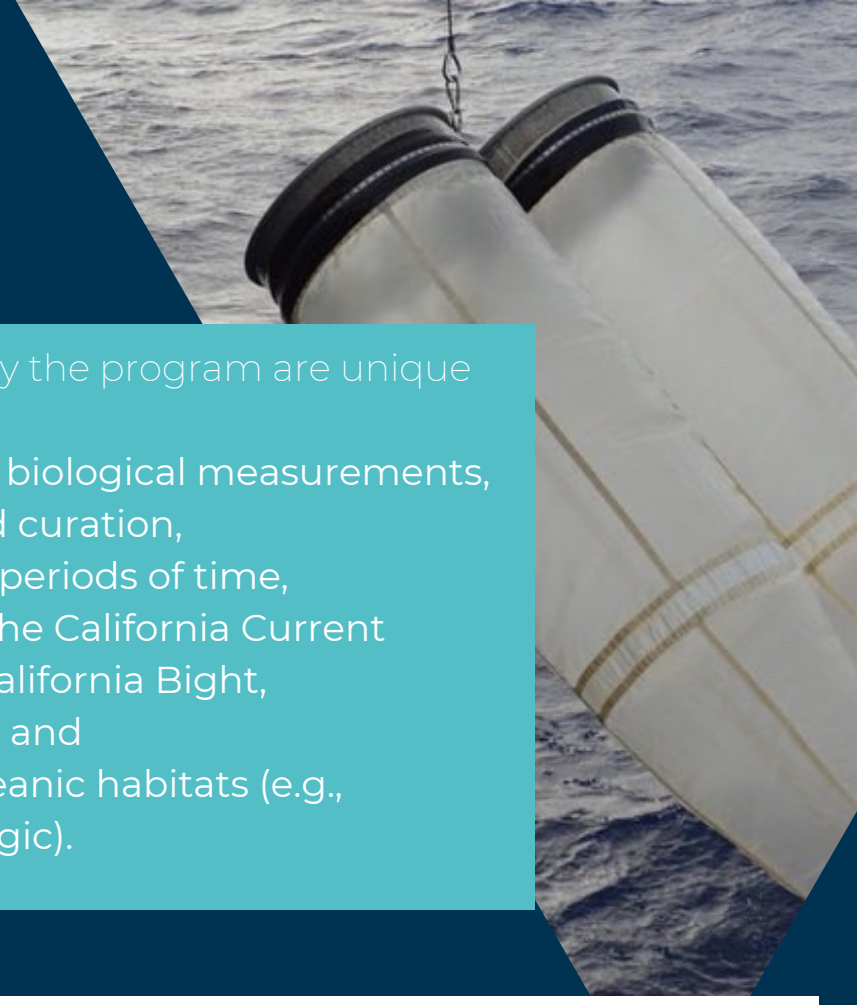


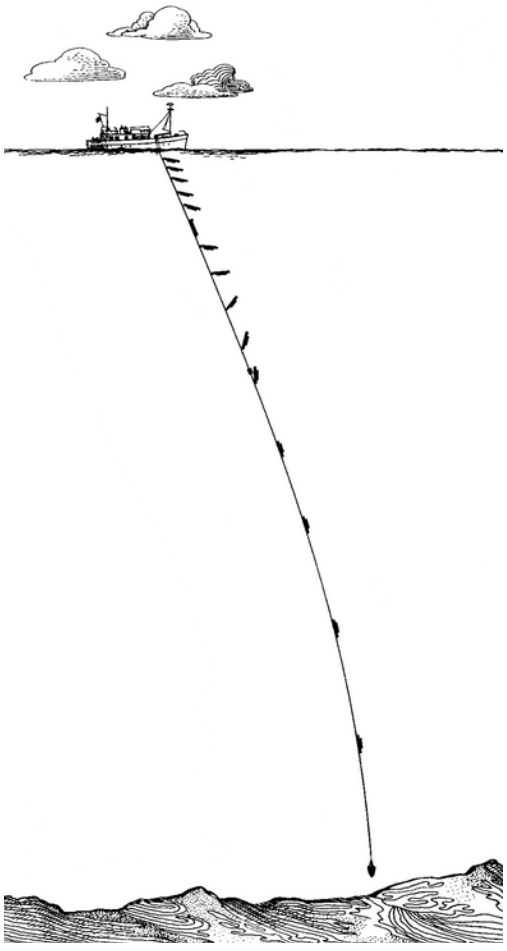
Figure 1. CalCOFI sampling locations along the California coast (reprinted from Engeman et al. 2020). CalCOFI sampling extends from Point Reyes south to San Diego and extends about 667 km offshore. CalCOFI samples in state waters (n = 13), federal waters (n = 83), and international waters (n = 8).

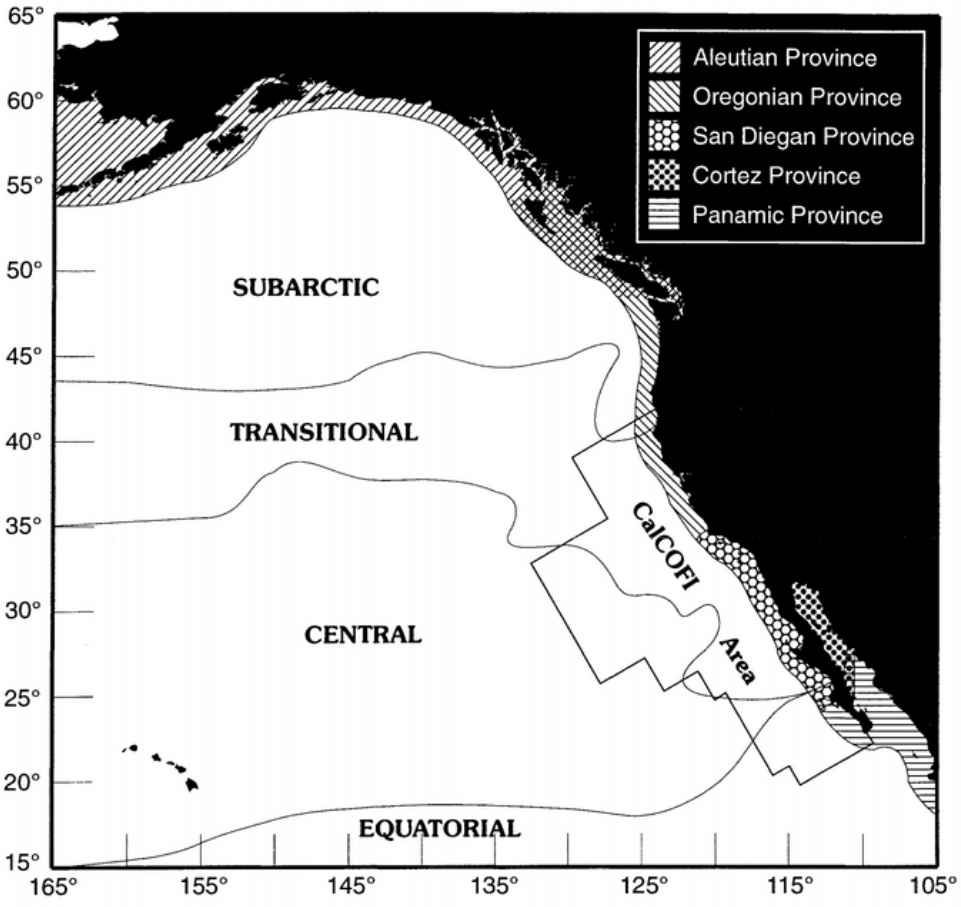
UNIQUE DATA & OBSERVATIONS



The data and observations gathered by the program are unique in that they are:

- integrated physical, chemical, and biological measurements, including sample preservation and curation,
- sampled seasonally and over long periods of time,
- observed within a large region of the California Current System and within the southern California Bight,
- sampled across numerous depths, and
- within various shelf/neritic and oceanic habitats (e.g., benthic, epipelagic, and mesopelagic).





COLLECT HIGH QUALITY, LONG-TERM, OPENLY ACCESSIBLE INFORMATION

The core CalCOFI program consists of data collection and processing by CalCOFI technicians (hereafter referred to as the core CalCOFI program), and includes oceanographic data, processed and managed by SIO, and ichthyoplankton data, processed and managed by NOAA's Southwest Fisheries Science Center (SWFSC). Long-term data that are collected as part of the CalCOFI ship operations, but are processed, analyzed, and managed by other labs, institutions, and organizations (hereafter referred to as collaborative programs). Collectively the core CalCOFI program and the collaborative programs make up the integrated CalCOFI program and sample over 50 different physical, chemical, and biological parameters (Figure 2, Appendix 1: CalCOFI Data Inventory 2021). The descriptions of the parameters below are inclusive of the parameters sampled by the integrated CalCOFI program, so include both measurements collected by the core and collaborative programs.

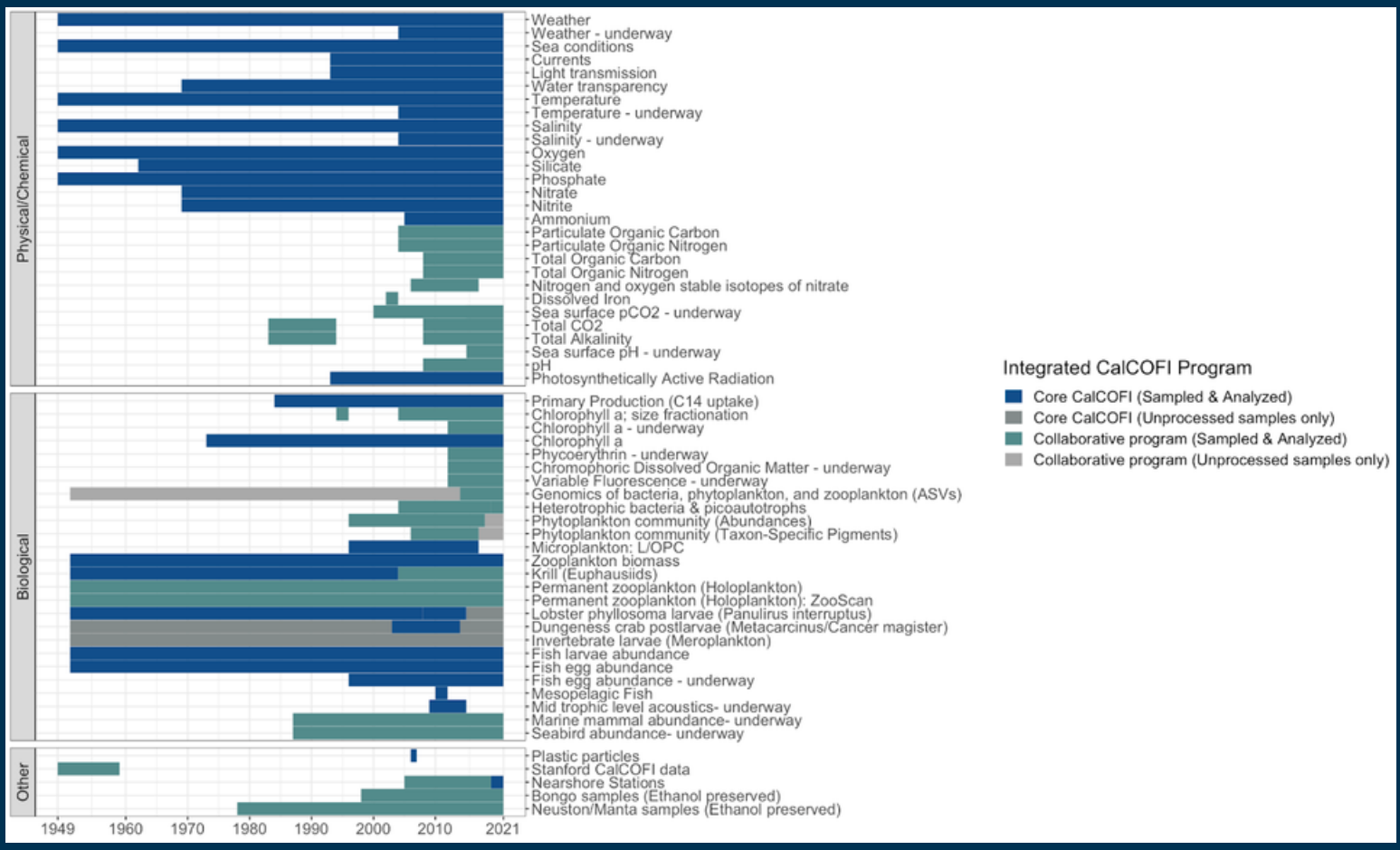
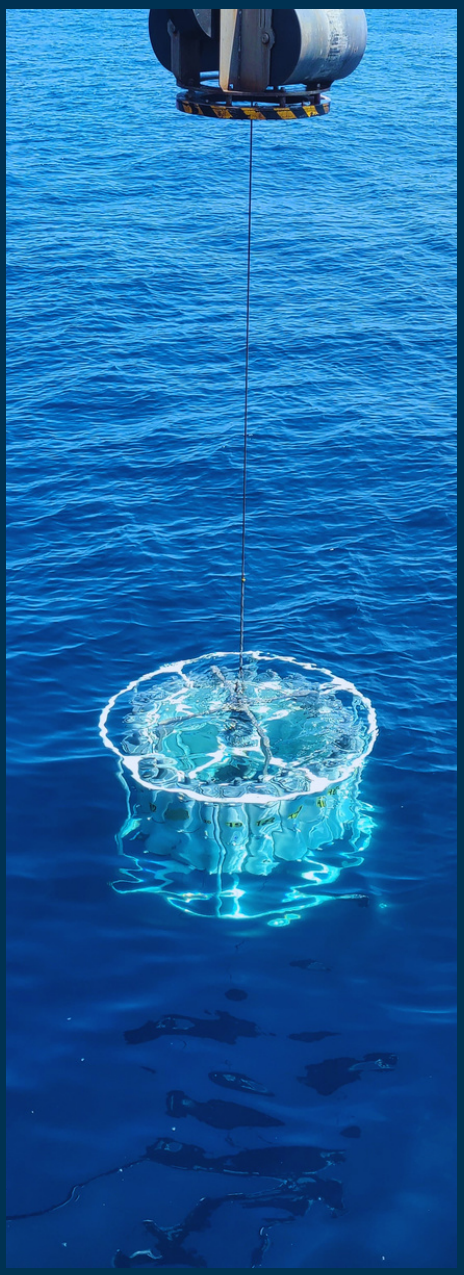


Figure 2. Timeline depicting the parameters collected on the CalCOFI platform and processed and analyzed by the Core CalCOFI program (blue) or by Collaborative Programs (teal). Samples that have been collected but not had support for processing and analysis are denoted in grey. Parameters are collected at each station, unless denoted by "underway".



PHYSICAL & CHEMICAL DATA COLLECTION

CalCOFI has collected environmental and hydrographic data for over 70 years including ocean temperature, salinity, dissolved oxygen, nutrients as well as inorganic carbon system measurements (e.g., TCO2, pCO2, pH, DIC) for nearly 13 years (since 2008). These data are collected using conductivity-temperature-depth (CTD) casts, Niskin bottles, and underway data (at 3 m depth) (Figure 3).

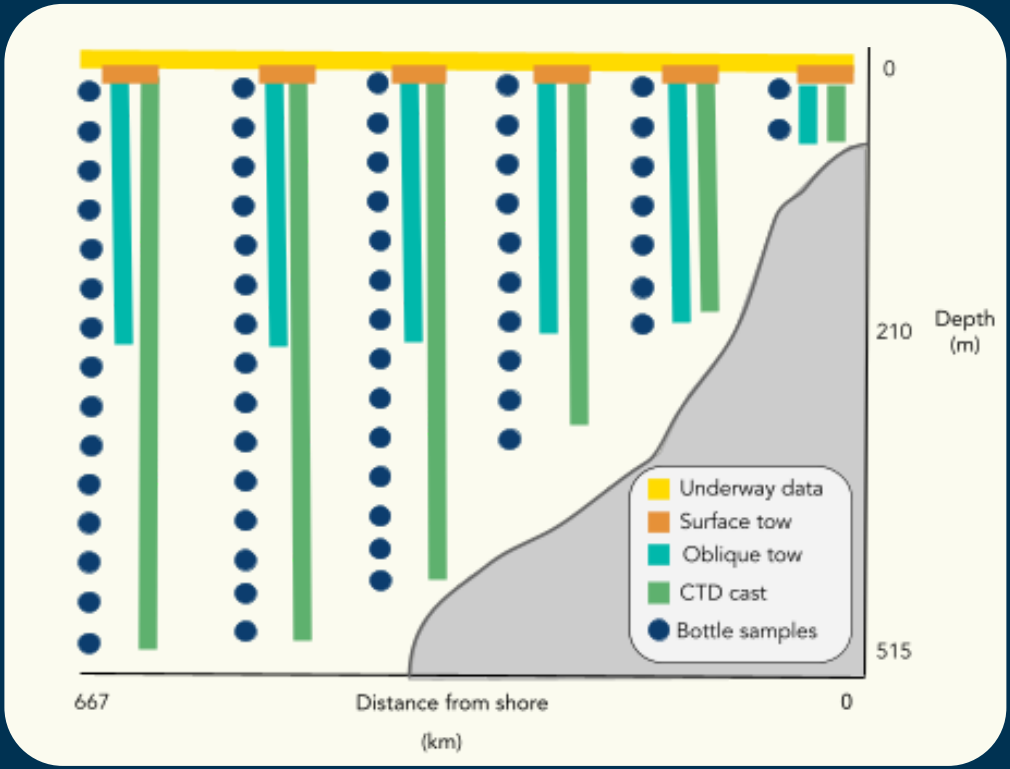
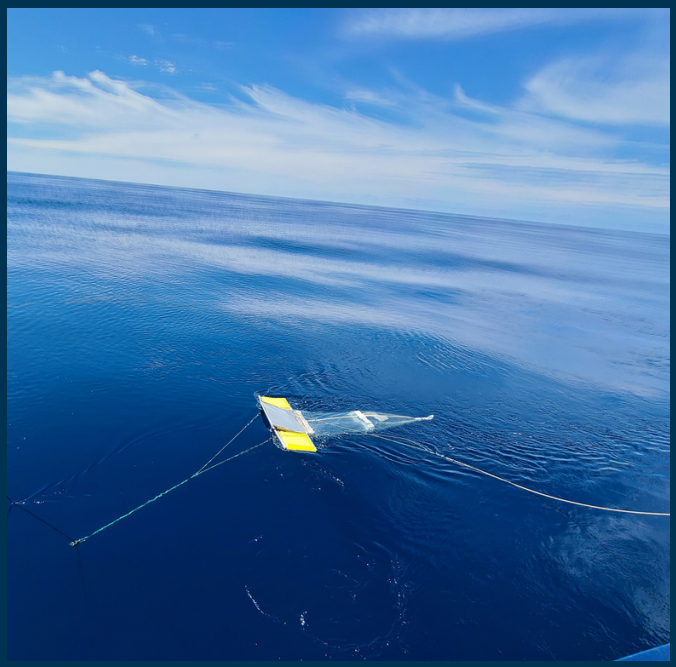


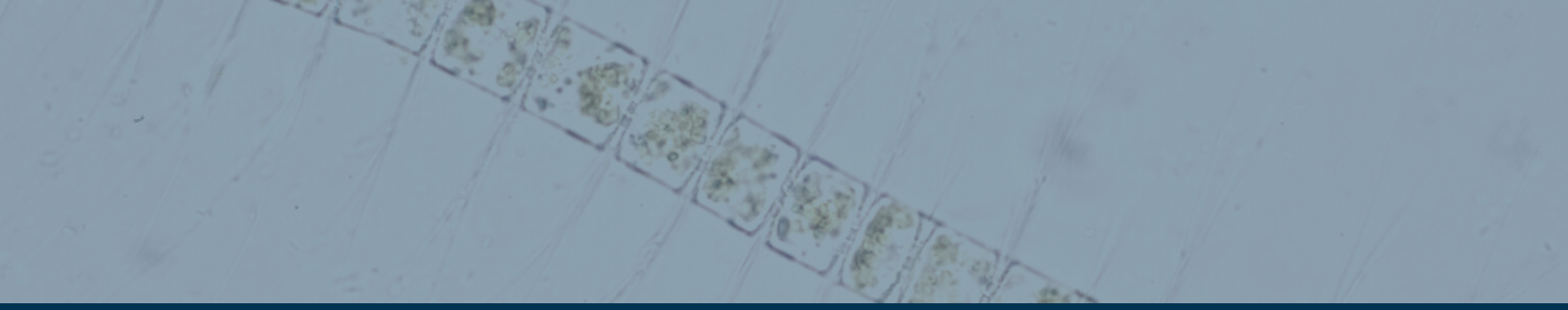
Figure 3. Visualization of select CalCOFI sampling locations across depths (not to scale).

The CTD (Seabird 911 plus CTD Rosette) profiles from the surface to the bottom (max depth 515 m) collecting temperature, salinity, oxygen, fluorescence, light transmittance, nitrate and photosynthetically active radiation (PAR). In addition, the CTD Rosette holds seawater sampling Niskin bottles (n = 24), which are closed at specific depths to collect seawater for oxygen, salinity, silica, ammonia, nitrite, nitrate and phosphate. In addition, weather observations, such as wave size, direction, and period measurements are taken by an observer at each station and supplement continuous sea surface data collected by the shipboard integrated measurement systems (MET/SCS). Water clarity measurements are taken by a Secchi disc during daytime stations.

BIOLOGICAL DATA COLLECTION

The biological data collected by CalCOFI and the associated collaborative programs have incredible taxonomic resolution. Specifically, visual abundance estimates of over 760 taxa of marine organisms (Appendix 2: Species sampled by CalCOFI) have been collected on the CalCOFI platform including, larval fish and egg data (~100 taxa) for 70 years; zooplankton abundance (~93 taxa), which consists of mainly holoplankton (e.g., krill, copepods, and other plankton that spend their entire life in the open ocean) for 70 years; marine mammals, seabirds, and turtles (~189 taxa) for over 30 years; primary productivity, phytoplankton biomass, and diversity (~374 taxa) for over 20 years; and microbes (e.g., Prochlorococcus, Synechococcus, and heterotrophic bacteria) for over 15 years. Invertebrate larvae have been collected continuously since the program's inception, but only some invertebrate larvae/meroplankton have been enumerated opportunistically in cases where there have been funds for an invertebrate sorter (e.g., California Spiny Lobster was sampled for over 50 years until 2008 and Dungeness crab postlarvae was enumerated from 2003-2014).





Bacterioplankton & phytoplankton

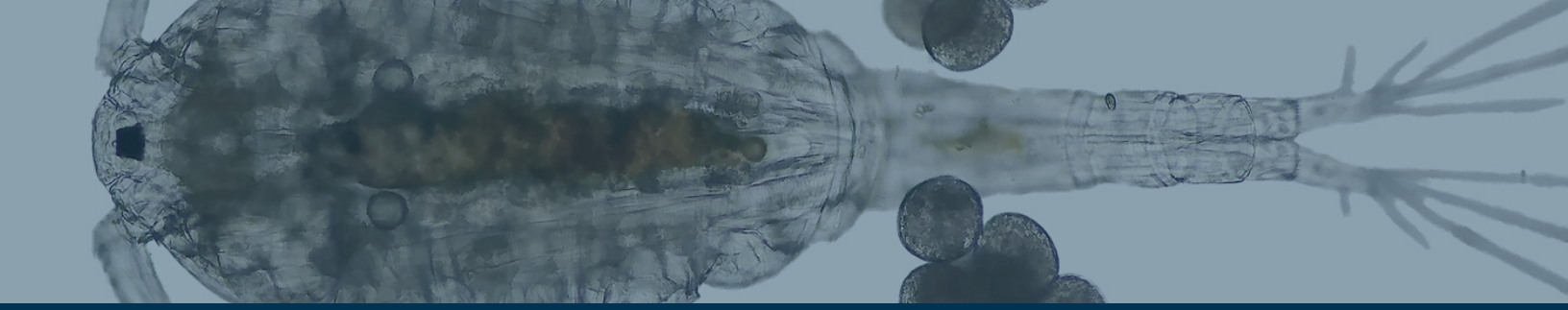
Bacterioplankton and phytoplankton have been sampled on CalCOFI cruises in partnership with the California Current Ecosystem Long-Term Ecological Research (CCE-LTER) and NOAA-CalCOFI Ocean Genomics program (NCOG) (*see Collaborative Programs*). Picophytoplankton populations and non-pigmented prokaryotes are sampled for abundances from 3 to 8 depths at and above the mixed layer. Seawater is collected from Niskin bottles and cells are fixed in the field aboard the survey cruises (since 2004) with paraformaldehyde, and stained with a DNA-specific dye back in the laboratory.

The cells are enumerated by flow cytometry to distinguish three major populations of photoautotrophs (Prochlorococcus, Synechococcus, and picoeukaryotes) and the assemblage of heterotrophic prokaryotes (bacteria). Concurrently, samples for measurement of particulate organic carbon and nitrogen are also taken. Samples are filtered and frozen at sea, and ashore in the lab they are acidified, dried and analyzed by high-temperature combustion. The results allow for the quantification of all living and dead planktonic particle carbon (C) and nitrogen (N), carbon-to-nitrogen (C:N) ratios, and the relative difference between the two pools.

Water is also taken for total chlorophyll a measurements from all sampling depths and stations as part of the core CalCOFI program. Additionally, the collaborative program samples size fractionated chlorophyll a is also measured from ~10m depth (surface layer) on line 83 and 87, with scattered inshore stations within the CalCOFI sampling grid (since 2006).

The size distribution of total chlorophyll a is determined by filtering water through filters of different pore sizes. These are then extracted in acetone and analyzed fluorometrically on CalCOFI cruises. Furthermore, chlorophyll a and taxon-specific pigments (chlorophylls and carotenoids) are qualitatively and quantitatively characterized in the lab ashore by several size fractions (< 1µm to > 20µm) utilizing High Performance Liquid Chromatography analysis. The samples analyzed are used to develop a metric for phytoplankton community structure to monitor its state and changes over time.

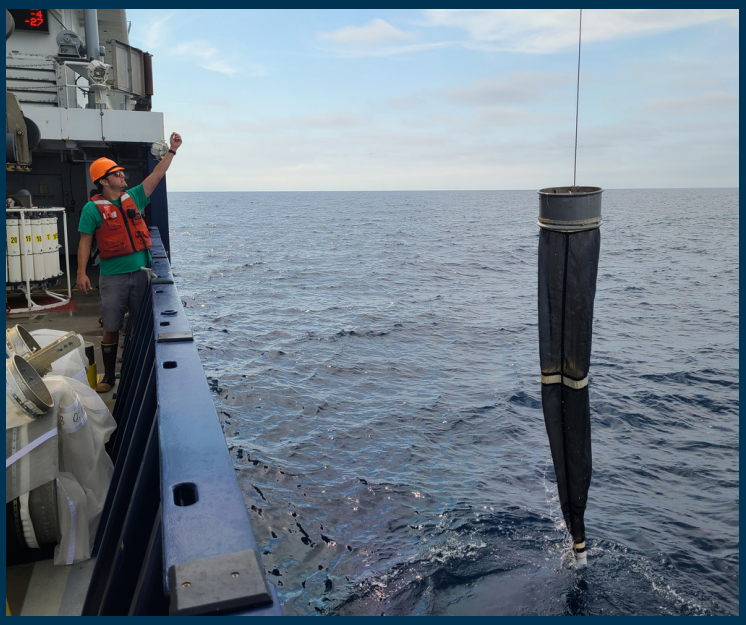
Since 1996, additional water samples from ~10m depth are taken from 34 stations spaced throughout the CalCOFI grid for enumeration of 386 taxonomic categories of phytoplankton, to the species level when possible, in collaboration with the Venrick Lab (see Collaborative Programs). The samples are preserved with 1% buffered formalin at sea, and returned to the lab where they were pooled into the four regional groups. Samples are analyzed by inverted phase-contrast microscopy. Lastly, the core program conducts primary production estimates through radioisotope (14C) labeling and on deck incubations at 6 in situ light levels on each cruise day. After ~12 hours incubation samples are filtered and filters frozen for later analysis of assimilated 14C back at the lab.



Zooplankton & Ichthyoplankton (larvae and eggs)

To sample the pelagic invertebrates and fish larvae, a few different nets are used to target different organisms and regions of the water column. To collect plankton at the surface (neuston), a Manta net (505 µm mesh size) is towed at the surface of the water for 15 minutes sampling the top 8 cm of the water column. To collect plankton throughout the epipelagic zone, a Bongo net (CalBOBL; 505 µm mesh) is used for an oblique (45 degree angle) plankton tow (max depth 210 m) (Figure 3). Bongo nets equipped with flowmeters consist of paired hoop nets, and contents of the starboard and port nets are preserved in formalin and ethanol, respectively. To further appraise the water column with a focus on quantifying fish eggs, a Pairovet net (150 µm mesh) is towed vertically from a depth of 70 m at locations from shore to station 70.

In addition, a Planktonic Rate Processes in Oligotrophic Ocean Systems (PRPOOS, 202 µm mesh) net is towed vertically from 210 m to collect mesozooplankton (planktonic animals in the size range 0.2-20 mm) on a subset of CalCOFI lines and stations (lines 90.0 and 80.0 all stations and lines 86.7 and 83.3 for stations less than 70.0), and data are analyzed in partnership with CCE-LTER (*see Collaborative Programs*). To sample fish eggs, the Continuous Underway Fish Egg Sampler (CUFES) pumps in and filters water during transit from 3 m depth. Contents of the CUFES filter are collected at regular intervals (e.g., 30 m), egg abundances are initially counted at sea and then verified on land. Acoustics data providing information on fish and macrozooplankton vertical distributions and density have been collected with a Simrad EK60 scientific sounder.



Marine mammals, seabirds, & sea turtles

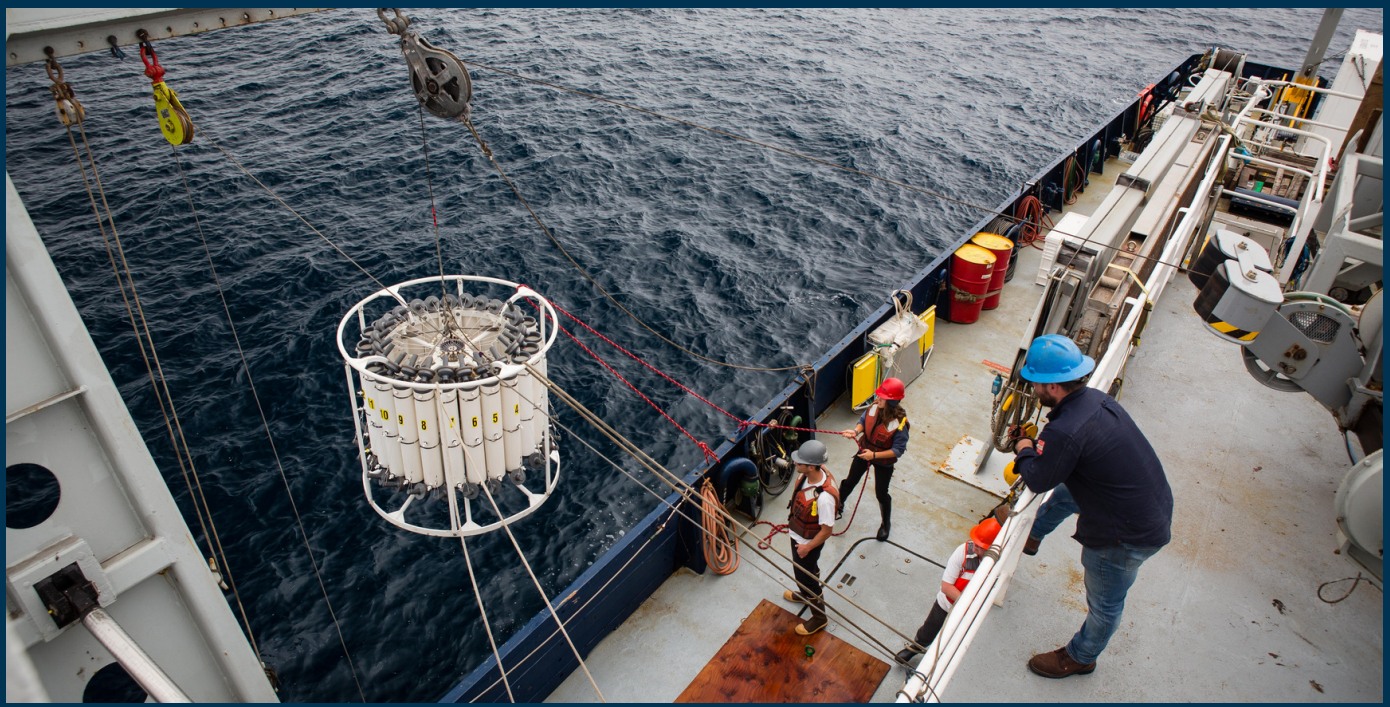
Marine mammals/birds/sea turtles observations are collected during transit between daytime stations in partnership with the Farallon Institute (birds) and the Scripps Institution of Oceanography Whale Acoustics Laboratory (marine mammals/sea turtles) (see Collaborative Programs). For marine mammal distribution and diversity, observers record location and species of all observed birds, marine mammals, and sea turtles.

Concurrently, acoustic technicians deploy autonomous drifting sonobuoys 1 nautical mile from each station. Additionally, long-term acoustic monitoring is conducted at seven CalCOFI stations using bottom-mounted, High-frequency Acoustic Recording Packages (HARPs). These data provide information on the annual and seasonal presence of cetaceans, and may be used to evaluate daily patterns of vocalization behavior.

Genetic data

CalCOFI, in concert with the NOAA-CalCOFI Ocean Genomics (NCOG) program (see Collaborative Programs), has collected water for genomic metabarcoding on over 30,000 - 40,000 single DNA sequences, known as Amplicon Sequence Variants. Metabarcoding quantifies sequence reads from taxa such as bacteria, archaea, diatoms, dinoflagellates, haptophytes, eukaryotic marine algae, and metazoans. The NCOG program has been sampling since 2014 and samples approximately 20 stations per cruise.

DNA has also been extracted from ethanol in which port-side bongo samples are stored. Similar to the NCOG water samples, this DNA is being metabarcoded to evaluate the efficacy of genetics to quantify fish abundances and inform how fish population assemblages change through time. Finally, rockfish larvae that cannot be identified based on morphology were Sanger sequenced to build species-specific time-series of rockfish assemblages.



DATA & SAMPLE ACCESSIBILITY

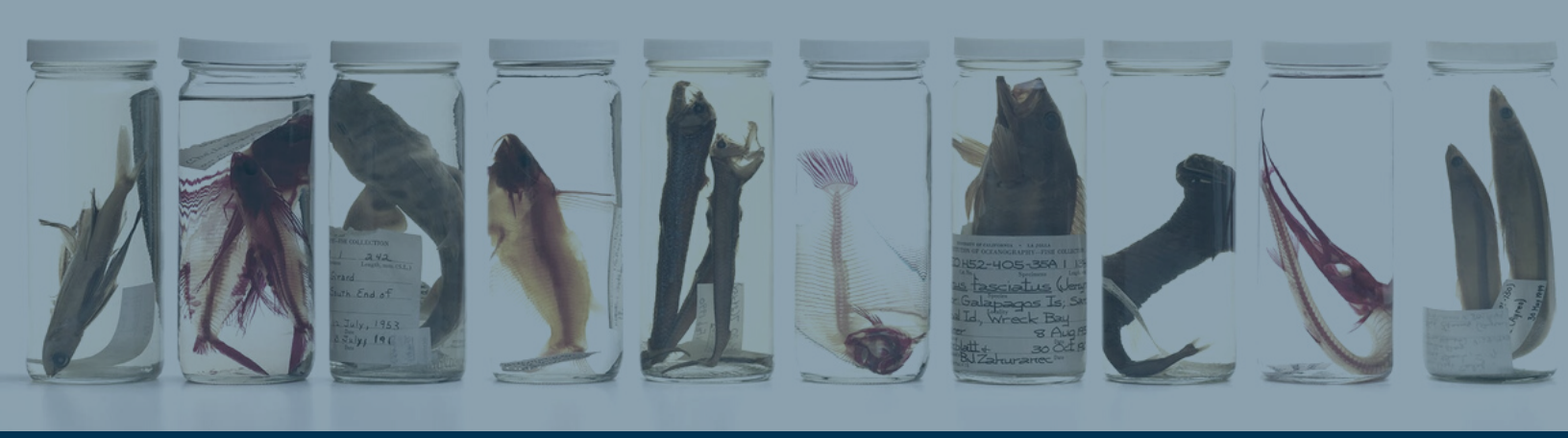
A central tenet of CalCOFI's mission is open science. Thus, CalCOFI works toward ensuring that all data, information, and knowledge generated through CalCOFI and the associated collaborative programs are transparent, accessible, and developed as a collaborative network where data and associated products can easily be linked and accessed. Previous publications have provided a detailed overview of the CalCOFI data management (Stocks & Baker 2005).

The CalCOFI data and samples are available to the broader science and practitioner community through openly accessible data serving platforms and sample archives. The data are licensed as CC-BY, which means that the data are openly available with a proper attribution. This is vital to ensure that CalCOFI data can be effectively translated into research, application (see Research & Management), and for education (see Educate). The technical teams and data management teams help to ensure the quality of the data and open sharing of the data (see CalCOFI Technical and Data management teams) .

All core CalCOFI data are analyzed and quality controlled within approximately 6 months of each cruise. The CalCOFI data are served via the CalCOFI web site for data processed by the SIO technical and data management teams and via the NOAA coastwatch ERDDAP server for data processed by the SWFSC technical and data management teams.

When staffing or access issues preclude the timely processing of ichthyoplankton net samples, the Spring and Winter cruises are prioritized for analyses because these are the seasons when most fish in the CalCOFI survey region tend to spawn or when spawning is at its peak.

Collaborative CalCOFI programs must conform to a CalCOFI data policy (calcofi.org/data-policy.html), which requires open access data sharing (not necessarily via CalCOFI data portals). For example, the access points to data collected in partnership with CalCOFI and collaborative programs include collaborative program websites, local data servers (e.g., CCE-LTER DataZoo), national data servers (e.g., Environmental Data Initiative and ERDDAPs, including Coastwatch, SCCOOS, and Oceanview), and international data servers (e.g., Ocean Biogeographic Information System- SEAMAP).



Archived samples

The CalCOFI program has built two of the world's largest collections of ichthyoplankton and zooplankton samples, curated at the Southwest Fisheries Science Center and SIO, respectively. The two sample collections represent irreplaceable archives of information about the biology of the California Current System for over 70 years.

The Southwest Fisheries Science Center ichthyoplankton collection includes all of the larval fish samples and species collected by CalCOFI since the late 1940s and is curated and managed by the Collection Manager (currently, Sherri Charter). These samples provide fisheries-independent measures of past population fluctuations, which are used by scientists and resource managers to evaluate population trends, their apparent drivers, and future projections. The sample archive also allows for retrospective analyses. For example, the species identities of many larvae were unknown at the beginning of CalCOFI, and the older samples are currently being visually reassessed to bring taxonomy to current standards. In addition, modern analytical tools such as stable isotope analysis and DNA metabarcoding are being applied to stored samples. All inquiries related to the SWFSC ichthyoplankton collection are directed to the SWFSC Collections Manager.

The SIO Pelagic Invertebrate Collection (PIC) has approximately 77,000 CalCOFI net samples curated and managed by the Collection Manager (currently, Linsey Sala). These samples include material collected by 1-m nets/Bongo, Calvet/Pairovet, and Neuston/Manta nets. The PIC houses both the formalin and ethanol preserved Bongo samples. There are also approximately 2,000 net samples archived in the PIC from the PRPOOS net collecting on CalCOFI quarterly cruises on behalf of CCE-LTER. Additionally, the cephalopod paralarval and planktonic spiny lobster phyllosoma sorted reference specimens from the CalCOFI 1-m net/Bongo samples are housed in PIC. All plankton samples are the property of CalCOFI, managed by the PIC.

Publically accessible code, methods, & best practices

In addition to data and samples, CalCOFI encourages and fosters an open science community that includes sharing methods, best practices, and code in order to support collaboration and innovation, provide reproducible results, and retain institutional knowledge.

CalCOFI shares detailed methods and protocols related to all aspects of sampling and cruise operations. These are regularly updated and accessible on both the CalCOFI and collaborative programs websites (e.g., CCE-LTER). For example, Checkley and colleagues (1997) describe the CUFES method to sample the distribution of pelagic fish eggs, which has been cited by over 216 times. As a leading program, other programs have adopted some of CalCOFI's methods over the years (e.g., MARMAP; Sherman 2019).

CalCOFI is working with the Ocean Best Practices (OBPs; Pearlman et al. 2019) programme of the IOC/UNESCO to share CalCOFI methods broadly with the international ocean observing and research community.

CalCOFI has recently created an organization on GitHub, a code hosting platform for version control and collaboration, and encourages the CalCOFI community to share code via this collaborative platform (CalCOFI GitHub organization).

For example, the CalCOFI Hackathon (see Educate) requires an open intellectual property agreement to participate so all code and associated products are available on GitHub, distributed in various repositories. In addition, all code from the UC Data Science Capstone projects (UCSB and UCSD) are available on GitHub. As of 2021, GitHub had 3,432 code files that use the term CalCOFI in over 13 programming languages and 31 public repositories with CalCOFI. For example, Whitmire (2019) has digitized and shared the CalCOFI data from the Monterey Bay region from the 1950s through Stanford University Libraries and the Collections as Data Facets project.

CalCOFI data are featured on Kaggle, which is a crowd-sourced platform that brings together data scientists from over 194 countries to solve data science, machine learning and predictive analytics problems. Kaggle has 23 shared notebooks and 1 dataset that feature CalCOFI .

SUPPORT RESEARCH & MANAGEMENT WITH CALCOFI INFORMATION

The CalCOFI data and samples are unparalleled globally in terms of their temporal extent, spatial coverage, and number of variables sampled concurrently and therefore are foundational to a number of research, policy, and management applications. The CalCOFI partners, collaborative programs, and CalCOFI community use the CalCOFI data to answer an array of essential research and management questions related to changes in coastal and pelagic marine populations, communities, and ecosystems in relation to climate change and variability, especially on topics relevant to the CalCOFI community (Figure 4). The information CalCOFI collects is guided by stakeholder input and CalCOFI continues to adapt sampling to meet stakeholder and community needs (see Engage).

Similar to the open data, metadata, and code (see Open Data & Samples), CalCOFI strongly encourages and supports the publication of open access publications using CalCOFI data in order to foster a culture of open science and generate knowledge applied to climate change and sustainability. Since 1950, over 10,000 professional publications have been published that use or cite CalCOFI data or mention CalCOFI. CalCOFI has openly published data and information in atlases, NOAA technical memorandums/data reports, and articles as part of the CalCOFI reports.

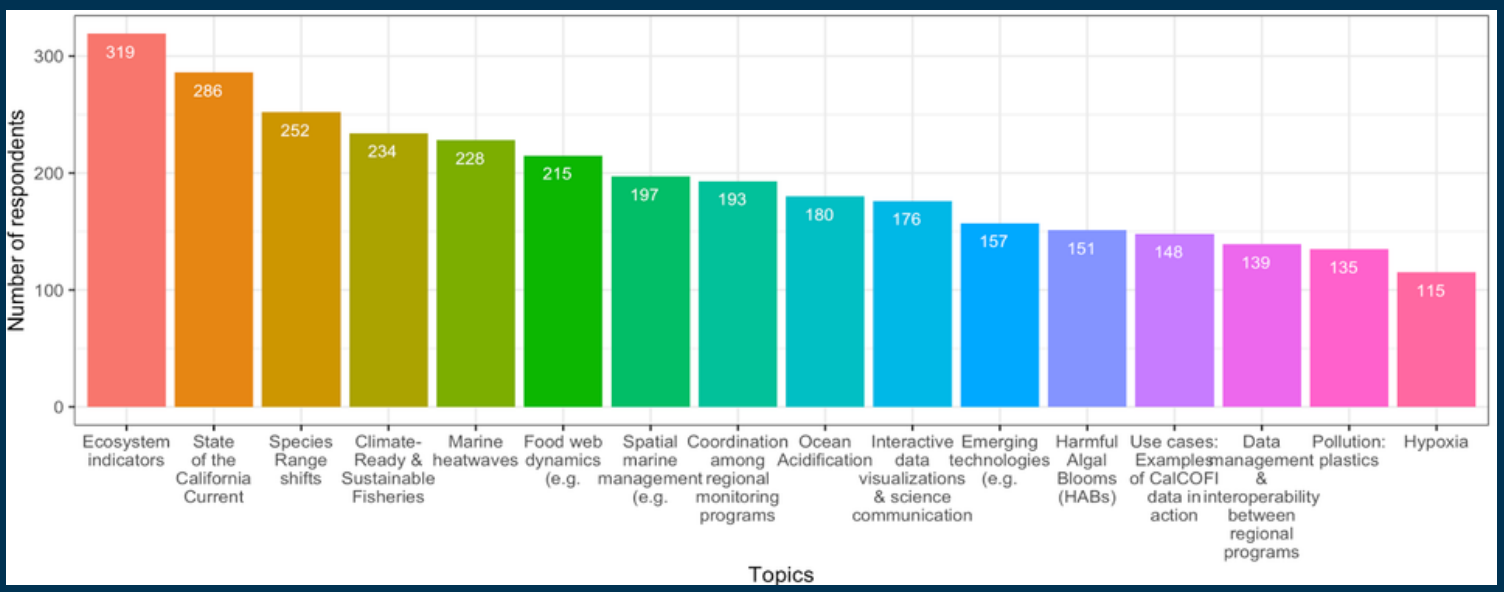
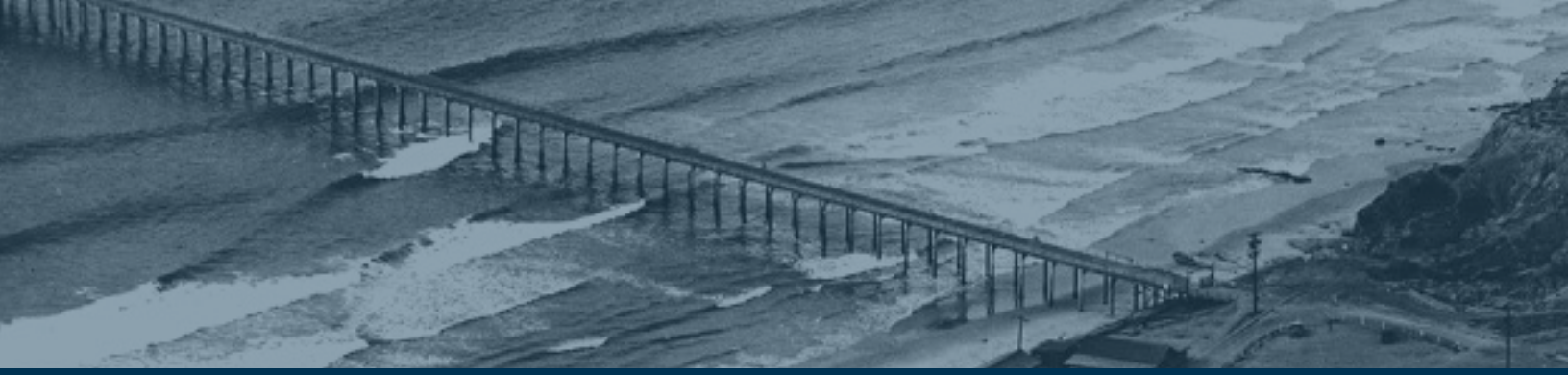
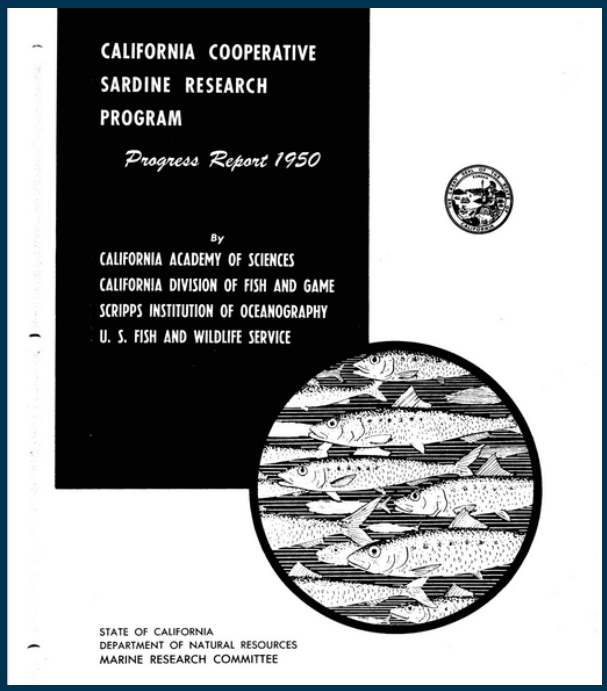


Figure 4. Topics of interest from the CalCOFI Community (n = 513) based on a survey of the participants at the 2020 CalCOFI Conference.



CalCOFI Reports

CalCOFI Reports began in 1950 as an annual report on the progress of the CalCOFI program. In 1960, CalCOFI Reports expanded to include peer-reviewed scientific contributions on marine research (not necessarily limited to CalCOFI data) and, since 1994, included an article synthesizing the oceanographic and biological conditions documented in the previous year by CalCOFI sampling, i.e., the State of the California Current Ecosystem Report, which currently includes physical and biological ocean observing data throughout the CCS. The journal CalCOFI reports retired in 2020 but the State of the California Current Report transitioned to the journal Frontiers in Marine Science (Weber et al. 2021).



CalCOFI supports the State of the California Current Report

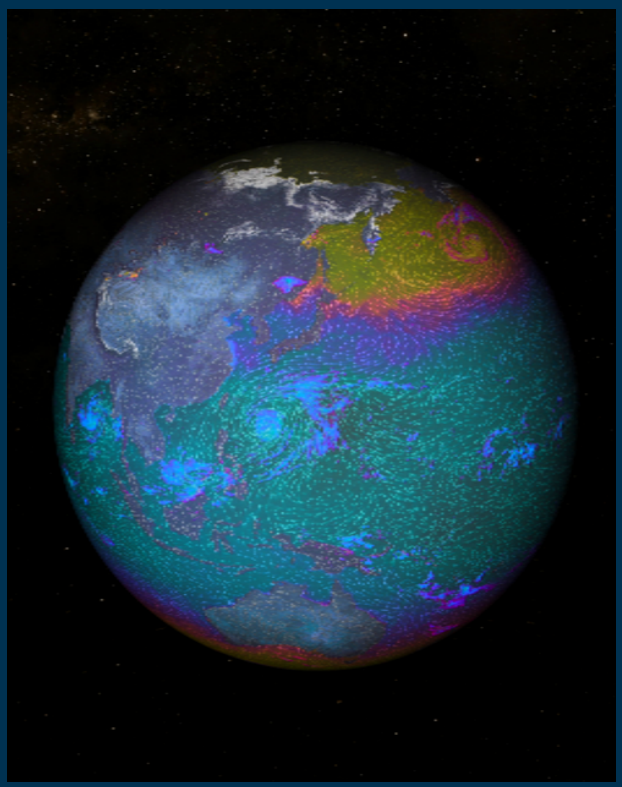
The annual State of the California Current Report synthesizes oceanographic and biological time-series data from the California Current Ecosystem. Original State of the California Current Reports focused on data collected by CalCOFI, but it has expanded to include a myriad of time series data throughout the CCS. Oceanographic measurements include basin-scale indices of ocean conditions (e.g., PDO, NPGO), regional environmental indices (e.g., upwelling), satellite data (e.g., sea surface temperature, SST), and depth-specific CTD data (e.g., temperature, oxygen).

Biological data consist of visual observations of seabird distributions and reproductive success, plankton tows that target ichthyoplankton and pelagic invertebrates, trawls targeting juvenile and/or adult fishes and invertebrates, visual observations of marine mammal abundances including detailed data on sea lion diet, count and reproductive success. Each State of the CCE Report attempts to contextualize biological responses (e.g., sea lion reproductive success) to major oceanographic events (e.g., marine heatwaves) in the previous year to provide CCE stakeholders an understanding of the overall condition of the CCE throughout the U.S. and Baja California, Mexico.

RESEARCH APPLICATIONS

The CalCOFI program has produced one of the most consistent and highest-quality long-term data sets to investigate the relationships between biological and physical/chemical processes (National Research Council 2001). Collecting physical oceanographic data (e.g., temperature, salinity) in conjunction with ocean chemistry (e.g., dissolved oxygen, pH) and biological samples (e.g., fish larvae and eggs, zooplankton) is vitally important to understanding multivariate stressors, tracking changing ocean conditions, and validating oceanographic models (Engeman et al. 2020). Thus, the CalCOFI data have been used to address research questions that require an integrated approach, such as fisheries, biological and ecosystem oceanography, physical oceanography, and chemical oceanography, as well as questions that require an extensive time series and spatial extent such as questions related to climate variability and change, species distribution and range shifts, or population and ecosystem dynamics.

The research applications below are listed in the order of what the CalCOFI community views as the most useful applications of CalCOFI data and samples including: climate change, fisheries, and marine ecosystem functions and services (fisheries, biological and ecosystem oceanography), fundamental insights into ocean conditions (physical and chemical oceanography), and marine pollution and water quality (Engeman et al. 2020). In addition, CalCOFI has helped to advance many sampling methods (e.g., CUFES) and calibration techniques (e.g., SeaWIFS).



Climate variability & change and the effects on marine ecosystems

A core and cross-cutting theme of CalCOFI is providing information to understand and predict climate variability, change, and the associated effects on marine ecosystems and coastal communities. In support of this, CalCOFI has been highlighted in many highly influential publications detailing the effects of climate change on marine ecosystems as a seminal long-term observing program (Doney et al. 2012, Poloczanska et al. 2016). CalCOFI provides essential data on ocean warming, ocean acidification, hypoxia/deoxygenation, which are climate stressors that have a large potential to affect the health of the California Current Social-Ecological System and the people that depend on it.

For example, increased ocean surface temperatures, stratification, and altered nutrient supply affect the planktonic food web and prey field for planktivorous fishes. These stressors also affect the duration and severity of harmful algal blooms (HABs) which cascades to have severe consequences for the entire social-ecological system, such as in the case of the widespread HAB event in 2015.

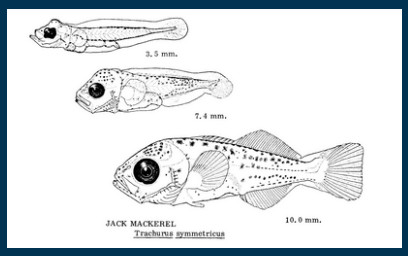
In addition, numerous modeling groups at research centers such as SIO, UC Santa Cruz, NOAAs Fisheries Science Center, and National Center for Atmospheric Research (NCAR) assimilate and use CalCOFI data in a variety of models that provide nowcasts and some forecasts for ocean state estimates. For example, CalCOFI measurements are used to evaluate model performance for coupled physical-biological-optics model development and simulation (Chai & Boss 2011).

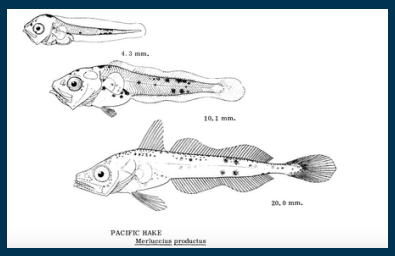
Over the years, CalCOFI data have been predominantly used to elucidate linkages between biological changes and broad-scale shifts in water masses (National Research Council 2001). This relates to fisheries and ichthyoplankton, zooplankton, marine mammal and seabird distributions and range shifts, and microbial ecology. Some specific applications of CalCOFI data to fisheries, biological, and ecosystem oceanography have been related to fisheries populations, communities, and ecosystem dynamics; plankton ecology and dynamics; and species distributions and range shifts.

Fisheries population, community, & ecosystem dynamics

CalCOFI has helped to show that the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) are dominant modes of natural ocean variability that can markedly influence fish stocks and their prey. For example, CalCOFI has helped to detail the impacts of El Niño on marine ecosystems such as on species range shifts and habitat compression of fish stocks, as well as on juvenile fish growth rates (Butler 1989), long-term changes in dissolved oxygen and its effect on demersal fish habitat, such as cowcod (McClatchie et al. 2010), and historical population fluctuations of fish, such as sardines and anchovies (Baumgartner et al. 1992) in the PIC (see Archived Samples).

The PIC supports scientific research by providing specimens for studies to advance research topics such as systematics, evolution, molecular genetics, ecology, biodiversity, population dynamics, trophic dynamics, and climate change. Many studies have focused on key organisms like euphausiids, copepods, pelagic tunicates, planktonic rhizaria (large protists), and 'synthetic plankton', also known as suspended microplastics. These long term records and resulting forecasting tools are helping to understand oceanographic phenomena like the impacts of ocean acidification, deoxygenation, and HABs on the pelagic communities. Extensive studies have documented the effects of El Nino Southern Oscillation (ENSO), Warm Anomalies, multi-decadal ocean variations, and secular ocean changes on the California Current System (Rebstock 2003).

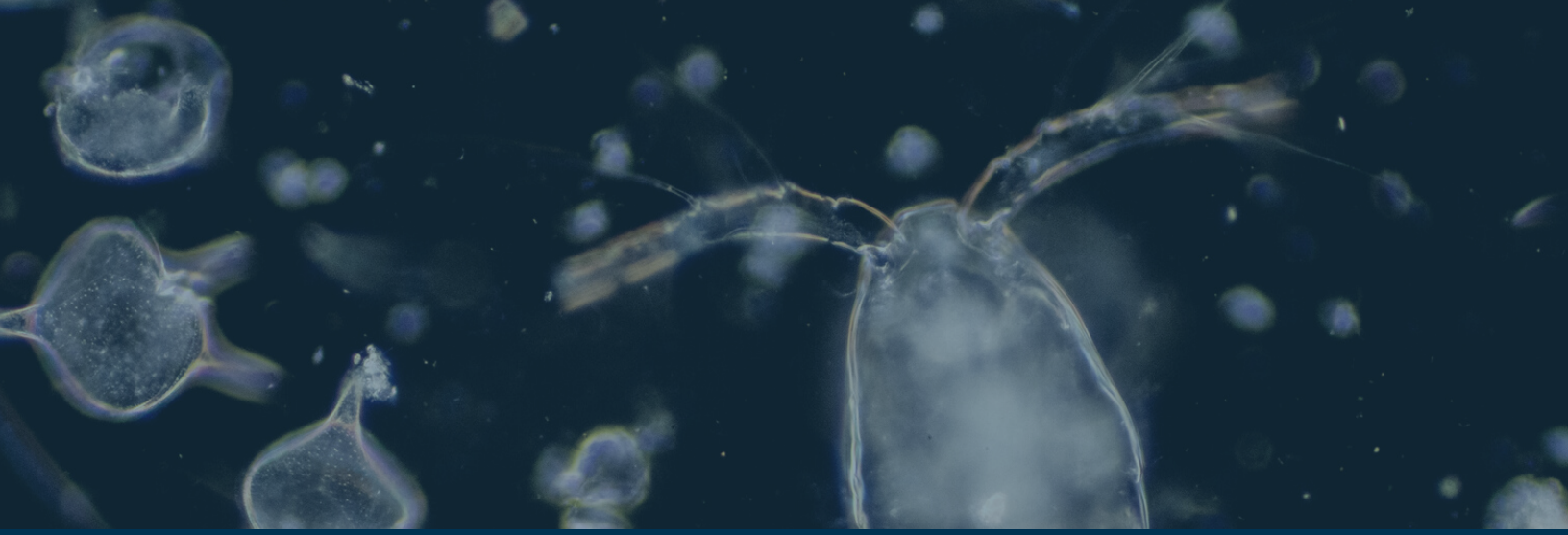




The fish larvae and eggs collected on CalCOFI cruises have significantly advanced the field of ichthyology and are invaluable in providing fisheries-independent, estimates of abundance, population dynamics and recruitment variability.

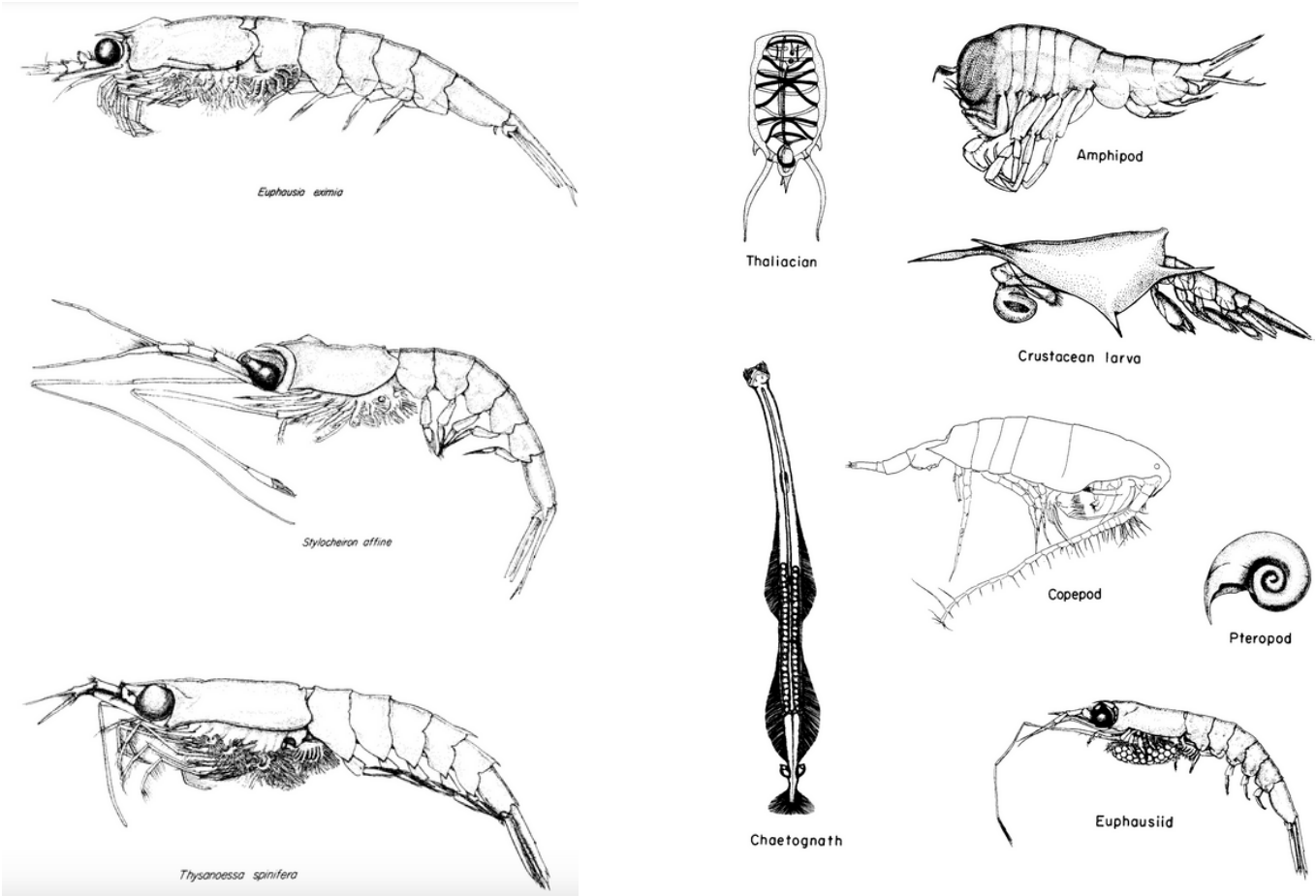
Within the CalCOFI community, there is wide support for CalCOFI's contribution to fishery life history data (Engeman et al. 2020). In the early days, CalCOFI researchers pioneered several important areas of marine research including: the taxonomy of fish eggs and larvae, the use of systematic surveys of oceanic areas for evaluating fish resources, the rearing of pelagic fish larvae, increased understanding of the hydrodynamics of plankton sampling gear, and studies on the responses of larval and adult fishes to their environment. CalCOFI has dramatically influenced the fields of larval fish taxonomy and ichthyology, and because of CalCOFI, 98 to 99 percent of fish larvae collected in the California Current region can be identified to genus or species. CalCOFI Atlas 33 serves as the primary taxonomic identification guide for larval fishes within the California Current.

CalCOFI has also contributed to vast amounts of information on the morphology, life history, and distribution of hundreds of species of marine fish eggs and larvae (Moser 1996) as well as on the feeding ecology of larval anchovy (Hunter 1972). CalCOFI has also supported the development of seminal theories such as the Stable ocean hypothesis (Lasker 1975) and the Basin theory for population expansion of pelagic fishes (MacCall 1990).



Plankton ecology & dynamics

Other studies have demonstrated multidecadal shifts in North Pacific pelagic ecosystems (Brinton and Townsend 2003; Lavaniegos and Ohman 2003), relationships between interdecadal warming of the California Current, increase in sea level, and concurrent decline in zooplankton biomass (Roemmich & McGowan 1995) and the relationship between large-scale ocean circulation and the biogeographic distributions of planktonic organisms (Reid et al. 1978). In addition, CalCOFI data have helped to show food web sensitivity to climate forcing and the effects of more localized perturbations, such as the fronts and eddies, as zones of enhanced prey availability as well as speciation mechanisms in oceanic plankton (Fleminger 1975; Goetze 2003).

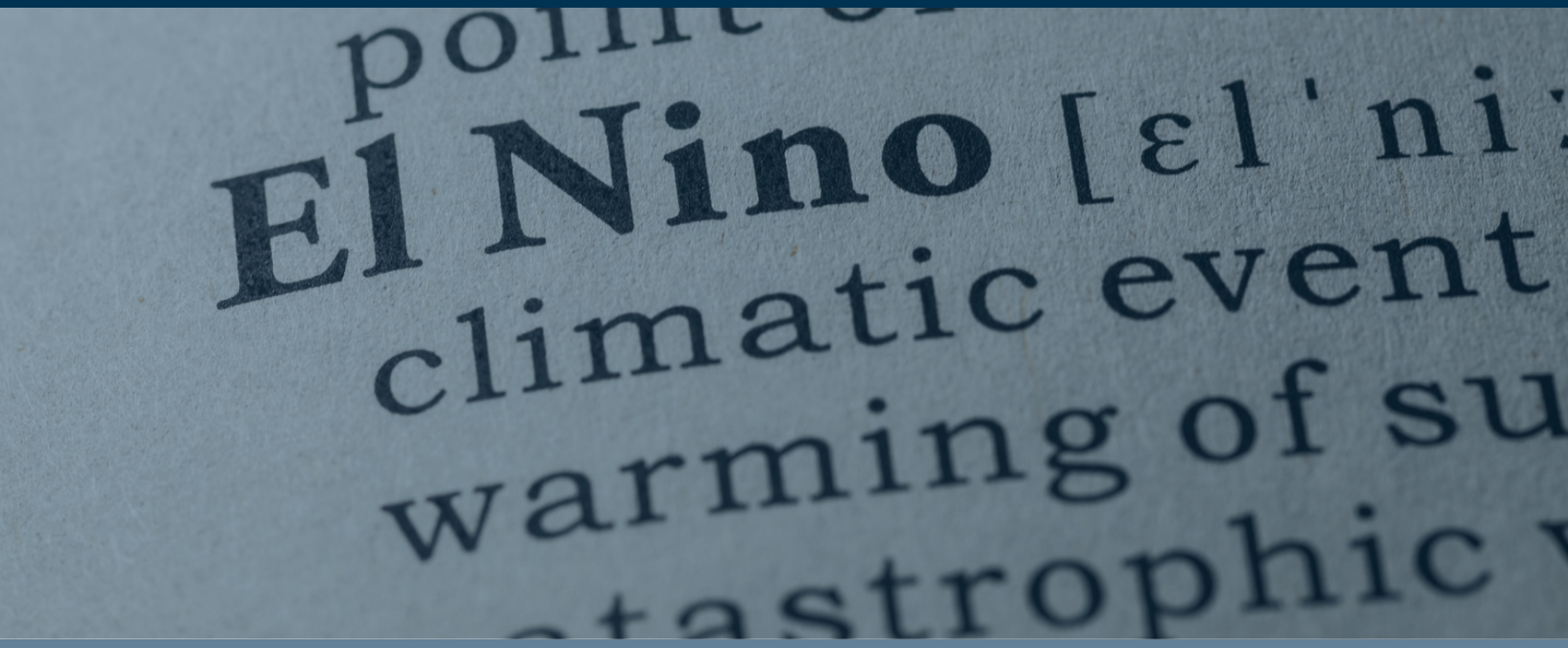


Species distributions & range shifts

Species abundances, collected as part of the CalCOFI cruises, have also been used to better understand changes in species distribution and abundance, especially in the context of climate change. For example, extreme mortality and reproductive failure of common murres has been shown to result from changes in extreme ocean conditions, such as the northeast Pacific marine heatwave of 2014-2016 (Piatt et al. 2020) as well as for projecting marine mammal distribution in a changing climate (Silber et al. 2017). In addition, CalCOFI data have been used in tandem with other long-term observations and participatory citizen science data to understand the episodic northward expansion of pelagic red crabs, Pleuroncodes planipes (Cimino et al. 2021).

Physical oceanography

The oceanographic data collected by CalCOFI has been used to understand the circulation of the California Current System (Bograd & Lynn 2003) and the links between climate oscillations (e.g., ENSO and PDO) and ecosystem change in the North Pacific (Di Lorenzo et al. 2008). CalCOFI has also been mentioned in book chapters on the physical oceanography of the Southern California Bight (Hickey 2020). CalCOFI data have been used to demonstrate that most of the temporal and spatial variability in the California Current System occur infrequently and over large areas and have revealed the connection between the shifts in coastal water masses and the periodic global-scale El Niño/Southern Oscillation phenomenon (National Research Council 2001).



Chemical oceanography

Data from CalCOFI cruises are increasingly being used to reconstruct spatial and temporal variations of the inorganic carbon chemistry of seawater that determines the solubility of calcium carbonate (Ω), including pH, total alkalinity (TA), pCO2, and dissolved inorganic carbon (Alin et al. 2012, Gallo et al. 2019). From 1984 to 2001 CalCOFI took samples for TCO2 and TAlk along CalCOFI line 90 which were analyzed by the Keeling and Dickson labs.

Underway pCO2 measurements date back to 2002, with the collaboration of MBARI and PMEL, supported by NOAA. In 2009, sampling to characterize the DIC system was resumed on a larger scale in collaboration with the Dickson lab at SIO. In 2015, Todd Martz (SIO) with support from CCE-LTER, built an underway pCO2 and pH system that has been used on all cruises since.

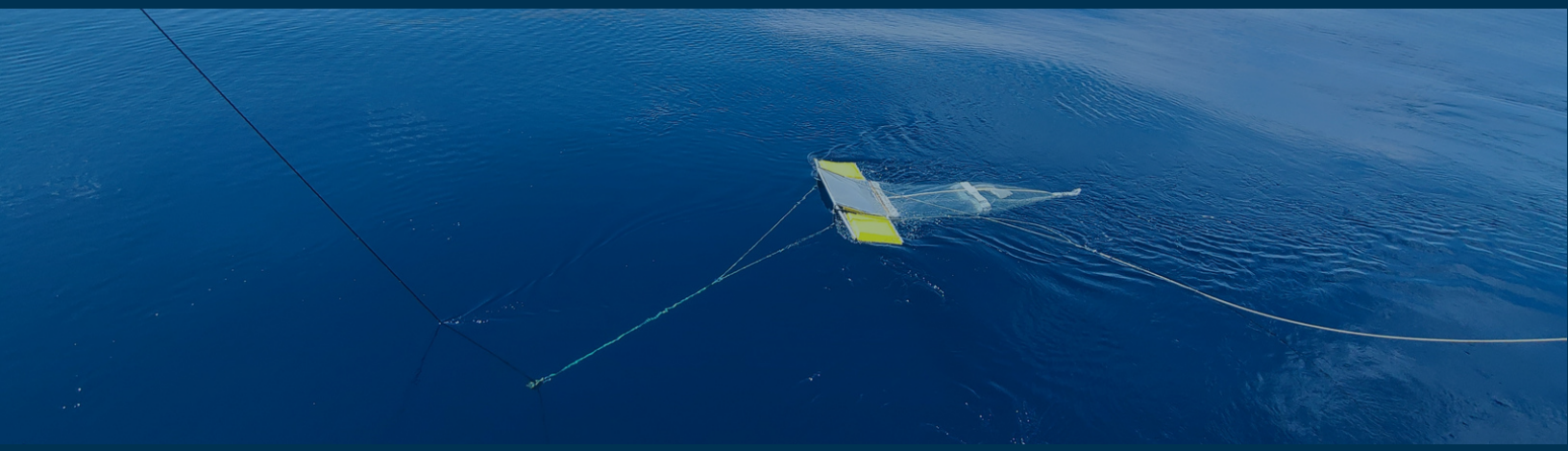
These measurements allow the complete resolution of the inorganic carbon system in the surface ocean along the cruise track and at selected stations across depths. CalCOFI, therefore, has both the historical time series and the current measurement capability to assess past, present and future spatially resolved OA in the southern California Current.

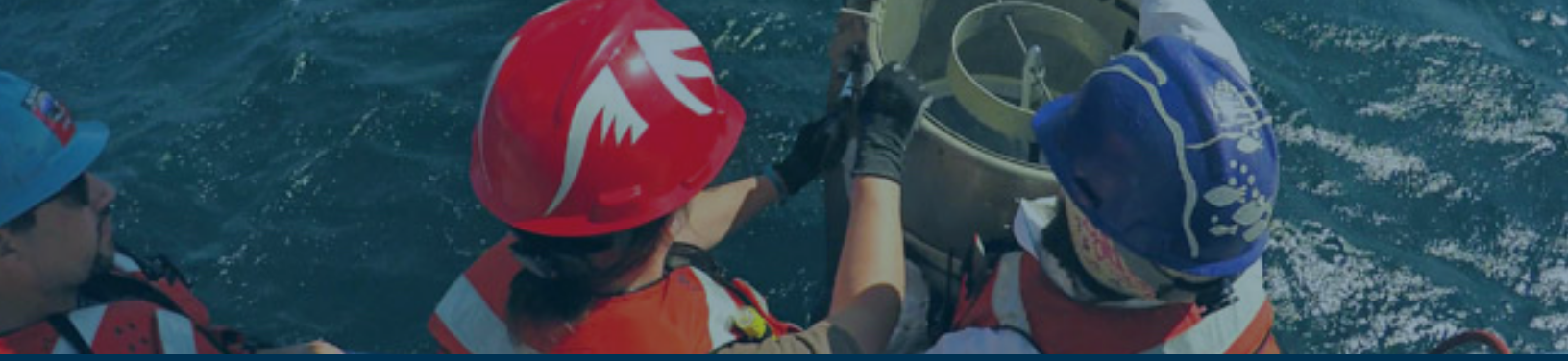
For example, biogeochemical sampling on the CalCOFI grid allows us to predict seawater pH and has shown that the surface layer in the nearshore (0 to 8 m depth) is rarely exposed to corrosive water (pH < 7.7). However, bottom waters (20 to 30 m depth) experience episodes of corrosive waters much more frequently, particularly in the spring and summer, such as during the upwelling season (Alin et al. 2012). In addition, CalCOFI has also been highlighted in book chapters on the chemical and geochemistry of the Southern California Bight (Eganhouse and Venkatesan 2020).

Water quality & pollution

Increasingly, CalCOFI data have been used for research on water quality and marine pollution related to bacterial contamination, plastic pollution, and manufactured chemical pollution. Stakeholders identified biological monitoring coupled with nearshore nutrient and bacterial pollutant sampling as an area of increasing importance for informing the management of nearshore fisheries and aquaculture, marine conservation areas, and understanding harmful algal blooms (HABs) (Engeman et al. 2020). For example, CalCOFI data have been used to understand micro- and nano- plastic pollution in the ocean, including documenting a dramatic increase in microplastics in the past 20-30 years, and ingestion by suspension-feeding zooplankton (Doyle et al. 2011).

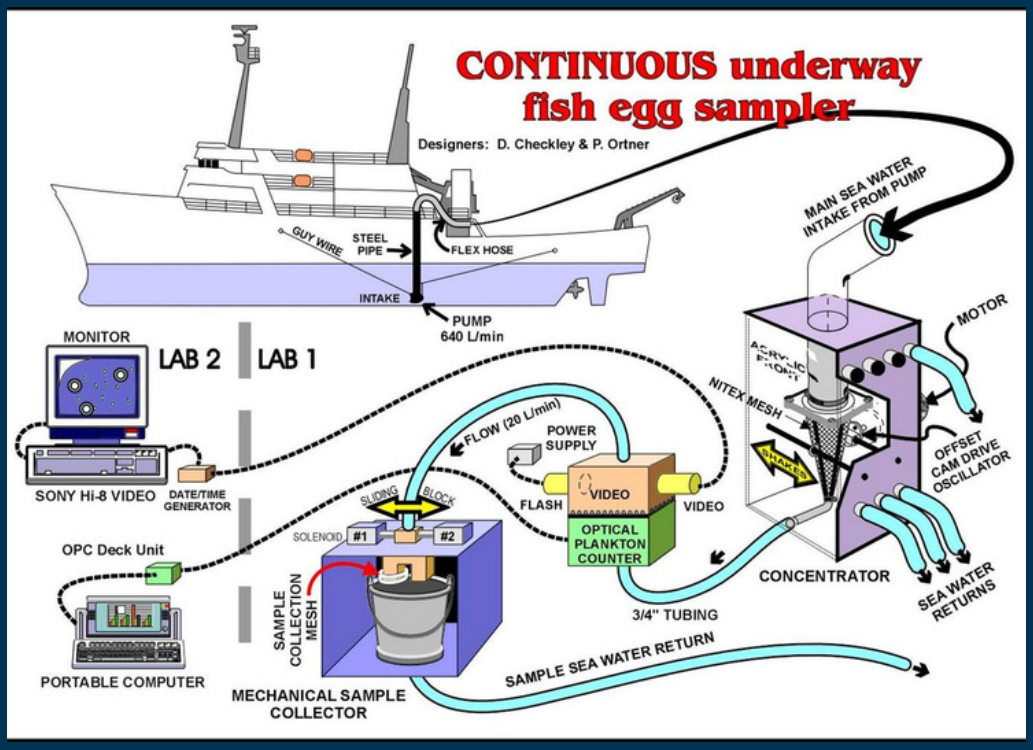
In regards to Harmful Algal Blooms (HABs), CalCOFI data have been used to provide oceanographic context for large HAB events (Trainer et al. 2020). In regards to manufactured and chemical pollution, there has been historical CalCOFI work on understanding the effects of DDT on pelagic food webs, including for plankton and fish, in the California Current (Cox 1972). Increasingly, there is a resurgence of interest at the state and federal levels to understand the effects of DDT contamination on the pelagic ecosystem in relation to a DDT waste site in the waters off of Southern California.





Calibration, methods advancement, & technology transfer

CalCOFI has significantly helped to advance many methods and calibration techniques, especially for fish and phytoplankton. For example, CalCOFI data was instrumental in the calibration of bio-optical algorithms for remote sensing of oceanic phytoplankton (O'Reilly et al. 1998, Kahru & Mitchell 1999), and the paper by O'Reilly et al. (1998) is the most cited CalCOFI paper having been cited over 2500 times. In addition, the Continuous Underway Fish Egg Sampling device and methods (CUFES) (Checkley et al. 1997) and the Ring Trawl CalCOFI plankton net were developed to research larger mesozooplankton as part of the CalCOFI program.

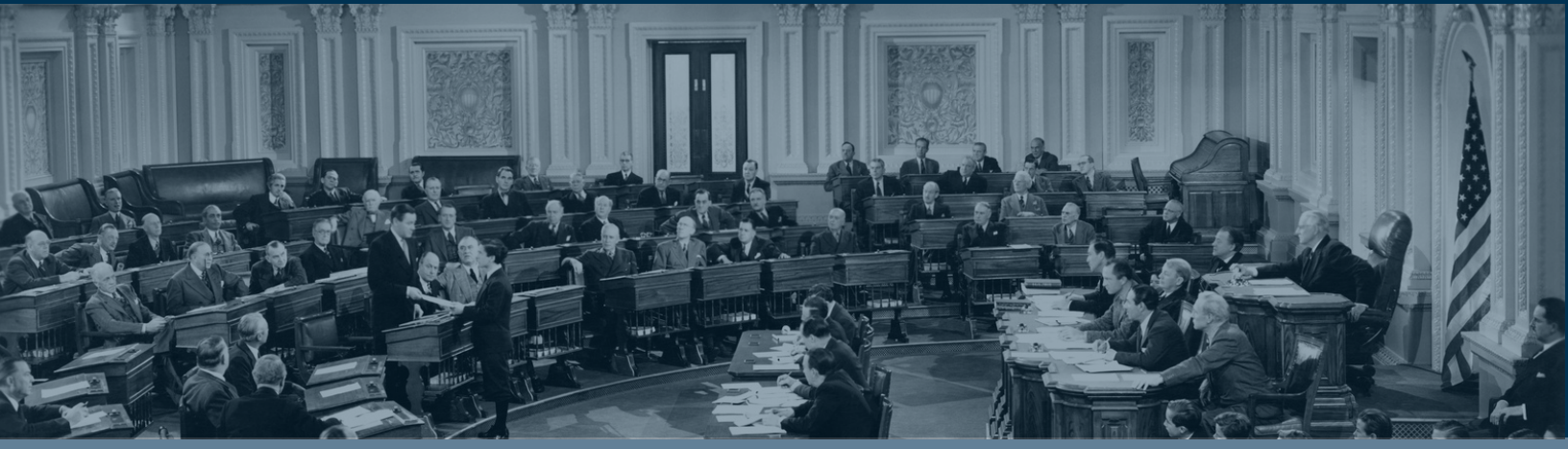


The Ring Trawl (CalCOFI) net is the standard plankton net for sampling large volumes of water for oblique or horizontal tows and has since been used internationally, such as by Flanders Marine Institute in the Helgoland Roads time-series (Greve et al. 2004). Other examples of CalCOFI advancements in ichthyology methods have been the development of the daily egg production method for estimating spawning stock biomass of epipelagic fishes (Lasker 1985), the methodology for quantitative sampling of ichthyoplankton (Smith and Richardson 1977), and the development of the objective definition of recurrent assemblages of plankton (Fager & McGowan 1963). Interestingly, the CalCOFI plastics studies (see Water Quality and Pollution) have helped to support the methods used for identification and quantification of microplastics in the marine environment (Hidalgo-Ruz et al. 2012).

POLICY & MANAGEMENT APPLICATIONS

Much of the research conducted by the CalCOFI community has been translated to numerous applications of policy and management. The policy and management applications are multifaceted, diverse, and cover local to international scales. Ocean observing, monitoring, and long-term research has continuously advanced in terms of technological capabilities as well as the ability to synthesize disparate sources of long-term spatiotemporal data. The US Commission on Ocean Policy (2004) identified ocean monitoring as a high priority for two reasons including to evaluate ocean and coastal ecosystem health and to detect changes over time and to enable managers to make informed decisions and adapt as needed.

Specifically, from its inception CalCOFI data have been used to support the management of sustainable fisheries and marine resources. In addition, since CalCOFI collects information on the entire marine ecosystem, CalCOFI data are relevant to biodiversity and ecosystem assessments; emerging ocean uses such as renewable energy and aquaculture; water quality, pollution, and human health; spatial marine planning; climate variability, change, and associated stressors; and to understand the broader oceanographic context of nearshore and coastal processes.



Food security: Sustainable fisheries

CalCOFI data support fisheries management by providing data and information relevant to individual species stock assessments and resource assessments as well as a broader understanding of ecosystem dynamics and long-term changes that inform ecosystem reports used in ecosystem-based management. In addition, CalCOFI provides information to management strategy evaluations (MSEs), fish management plans (FMPs), and enhanced status reports (ESRs).

CalCOFI collects data on larval fish, select invertebrates, and adult sharks via net tows and visual observations. Of the species that have been identified and enumerated on CalCOFI cruises, CalCOFI has collected data on over 40 fish, shark, and invertebrate species directly relevant to the Magnuson-Stevens Act and California's Marine Life Management Act (Appendix 3: CalCOFI management relevant species).

However, most invertebrate larvae have not been qualitatively enumerated in the CalCOFI samples and those that have have been of limited duration (California spiny lobster larvae, Dungeness crab postlarvae, and market squid paralarvae). Yet qualitative evidence suggests that there are numerous additional invertebrate larvae and other plankton species that could be very important to management, such as several crab species. Thus, retrospective analyses of the archived CalCOFI samples likely will reveal larvae of invertebrate species that are important to state fisheries species and could be used to develop abundance indices. In addition, retrospective analysis of collected samples could also provide important information on prey resources and trophic energy pathways for managed fisheries species, which can be essential to stock-recruitment assessments, such as for the Northern Anchovy.

Larval fish abundance trends are considered a proxy for spawning stock biomass and can therefore serve as a fishery-independent index of abundance. Such indices, when compared to landings information, can help to disentangle fishery and environmentally induced changes in abundance. The consistency of samples of harvested species across the CalCOFI time series provides insight into the trends in larval fish community composition, the arrival of new species into the California Current System, and the recovery of previously overfished species. For example, the NOAA Fisheries CalCOFI Ichthyoplankton Ecology team and scientists in the Coastal Pelagic Species team of the California Department of Fish and Wildlife utilize CalCOFI data to support analysis and synthesis related to coastal pelagic species.

For stock assessments, CalCOFI data has provided key data on fish larvae and eggs, as well as environmental data for stock assessments of Pacific Sardine (Kuriyama et al. 2020), Pacific Mackerel (Crone et al. 2019), and Northern Anchovy (PFMC 2020).

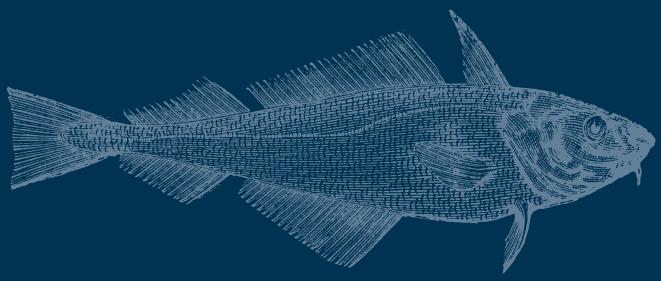
Namely, the offshore temperature CalCOFI records are used to establish annual harvest guidelines for Pacific Sardine, known as the Pacific Sardine management harvest control rule. As of 2017, the Pacific sardine harvest guideline (HG) control rule was revised to use a 3-year average of ocean temperature data from CalCOFI survey, rather than temperatures measured from the end of the SIO Pier, in order to better reflect the best available science (Federal Register 2017). Several stock assessments are partially fitted to CalCOFI larval fish based on indices of abundance. These include assessments for several species for which larvae can be morphologically identified to species such as rockfish (Moser et al. 2000), Bocaccio (He & Field 2017), Shortbelly rockfish (Field et al. 2007), Northern Anchovy (Jacobson et al. 1994), Pacific sardine (Hill et al. 2015), California sheephead (Alonzo et al. 2004), California scorpionfish (Monk et al. 2017), and Cowcod (Butler et al. 1999). CalCOFI data have been considered for use in blue rockfish assessments and for a California halibut assessment that is currently in progress. In addition, CalCOFI data, especially the larval fish data, are used to inform other West Coast fisheries management, such as the Fishery Management Plans for Groundfish of the Gulf of Alaska (2020) and the Oregon Forage Fish Management plan (2016) and have also been used in the absence of stock assessments (e.g. Grunion data).

Aside from formal management implementation through assessments and Fisheries Management Plans, CalCOFI larval data has informed management decisions for many other species. For example, paralarvae caught in CalCOFI bongo nets have provided fishery-independent measures of market squid stock size. Also, the time series of larval Pacific hake from CalCOFI has been used to understand the stock's relationship to environmental factors and has been considered for use in stock assessments (Helser & Martell 2007). In addition, Koslow et al. (2012) found the abundance of early stage California spiny lobster larvae (phyllosoma) to be positively correlated with environmental factors and suggested phyllosoma could be a useful indicator for management. CDFW staff continue to update these analyses to help guide decision-making in the event that reference point thresholds identified in the Fisheries Management Plans are crossed.

Ecosystem-based management

CalCOFI supports ecosystem-based management through the California Current Integrated Ecosystem Assessment (CCIEA) report (2021) which uses the CalCOFI data and the State of the California Current Report produced by CalCOFI (Weber et al. 2021) to describe the annual state of the California Current System including physical variables (e.g., oxygen, sea surface temperature, salinity) and biological indicators (e.g. forage fish/larval fish, birds). Specifically, the PFMC Fisheries Ecosystem Plan calls for annual ecosystem status reports (ESRs) that summarize the status and trends of key indicators of physical, ecological, economic and social conditions in the CCE and provide the PFMC with context for ecosystem-based decision-making (PFMC 2013). These ESRs build directly on the CalCOFIs State of the California Current Report. Recently, CalCOFI data and reports were included in the Pacific Coast Fishery Ecosystem Plan (PFMC 2021).

International fisheries policy



At an international level, in 2020 the Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States and Canada explored the CalCOFI larval hake production index (1951-2006) as a potential index of hake spawning stock biomass (Helser & Martell 2007).

Potential Users of CalCOFI for application to fisheries

Primary users of CalCOFI data and reports for fisheries management are the California Department of Fish and Wildlife, NOAA, the Pacific Fisheries Management Council, the North Pacific Fisheries Management Council, Oregon Department of Fish and Wildlife, and Washington Department of Fish and Wildlife.

Marine Ecosystem Assessments

The information generated by CalCOFI supports holistic ecosystem assessments, ecosystem status reports, condition reports, as well as Environmental Impact Assessments, which are mandated as part of the National Environmental Policy Act.

For example, NOAA's Office of National Marine Sanctuaries produces standard condition reports as a tool to periodically assess a sanctuary's "state," specifically related to the current status and recent trends of driving forces, human pressures, water quality, habitats, and living resources, as well as providing information to the Management Plans for the sanctuaries. CalCOFI also contributes to the monthly reporting on NOAAs West Watch Regional Environmental Conditions and Impacts in the West.

In addition, CalCOFI collects data relevant to many endangered species policies and conventions. CalCOFI collects data on 35 individual marine species that are listed as Threatened or Endangered species (Endangered Species Act) or protected under the international Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), international designated Specially Protected Areas and Wildlife (SPAW), national Marine Mammal Protection Act (MMPA) (n = 34 marine mammal species) (Appendix 3: CalCOFI management relevant species). Overall, CalCOFI collects data on over 75% of marine threatened and endangered species along the west Coast.

International biodiversity policy

At an international level, CalCOFI data contributes to the Global Ocean Observing System, Global Climate Observing System, and the Marine Biodiversity Observing Network through the associated Essential Variable framework (EOVs, ECVs and EBVs, respectively). The EV frameworks provide a mechanism to support biodiversity indicators for the Aichi Targets within the United Nations (UN) Convention on Biological Diversity (CBD) (Miloslavich et al. 2018, Muller-Karger et al. 2018). In addition, the CalCOFI reports were cited in a paper by the High Level Panel for a Sustainable Ocean Economy on "Critical Habitats and Biodiversity: Inventory, Thresholds and Governance' (Rogers et al. 2020).

Potential Users of CalCOFI for application to ecosystem assessments

The NOAA Integrated Ecosystem Assessment team, West Coast National Marine Sanctuaries including Channel Islands, Gulf of the Farallones, Monterey Bay, and Cordell Bank), Port of San Diego, and the California Coastal Commission.

Effects of ocean uses on marine ecosystems

Increasingly, CalCOFI information is being used to provide baseline assessments related to ocean use projects and activities, such as the effects of renewable energy projects or naval operations on marine species. This is especially relevant for Threatened and Endangered species, marine mammals, seabirds, and Essential Fish Habitat. For example, CalCOFI observations have been used to understand the environmental setting of the Southern California Outer Continental Shelf Planning Area, specifically related to the behavior, distribution, abundance, and diversity of whales, dolphins, and porpoises (Argonne National Laboratory 2019). Similarly, BOEM's Environmental Studies Program (Outer Continental Shelf) used the State of the California Current report to inform their final report on the California Current System (Moore 2021).

Naval operations

In addition to renewable energy, CalCOFI data have been used to understand the effects of naval operations on marine mammals. Specifically, CalCOFI marine mammal sightings data have been turned into marine mammal density estimates (Becker et al. 2017) and integrated into habitat models. These marine mammal density estimates are provided via reports and technical memos (Debich et al. 2017) then integrated into the 'take' statistics for the US Navy's marine-based exercises. For example, CalCOFI information was used to inform the Point Mugu Sea Range Environmental Impact Statement.

Aquaculture

CalCOFI data are increasingly being used for siting and feasibility assessments of offshore aquaculture facilities. CalCOFI data are especially useful in this context, because the data are depth resolved and extend out farther offshore, past the continental shelf, than most other sampling in the California Current (Figure 5). For example, an assessment to understand the suitable and optimal living conditions for the California mussel (*Mytilus californianus*) was conducted using water column data from CalCOFI (Reynes 2013). CalCOFI data have been used to monitor and evaluate concerns related to the environmental sustainability of offshore aquaculture. For example, CalCOFI was highlighted in an analysis of potential environmental impacts associated with the Rose Canyon Fisheries, Inc. (RCF) Sustainable Aquaculture Project. The project would have represented the first commercial-scale, offshore fish farm in the federal waters of the US. Specifically, CalCOFI data were used in the assessment of water-quality parameters (e.g., nutrients, dissolved oxygen, and light penetration).

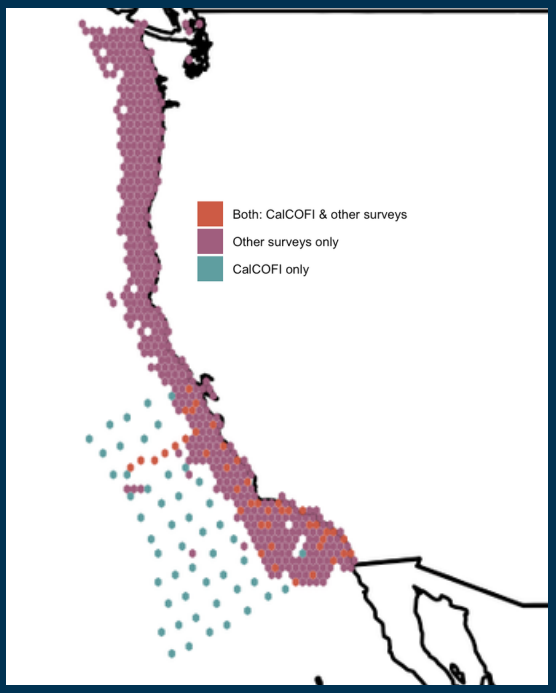


Figure 5. Sampling of CalCOFI stations relative to other long term biological observing programs off the U.S. West Coast. CalCOFI is one of the only programs to sample in the offshore environment (blue) and provides essential oceanographic and marine ecosystem context to the other programs in the California Current System (purple).

Potential Users of CalCOFI for application to understanding the effects of ocean uses on marine ecosystems

CA Energy Commission, HT Harvey and Associates, BOEM, Marine Mammal Commission, U.S. Navy, and USGS.

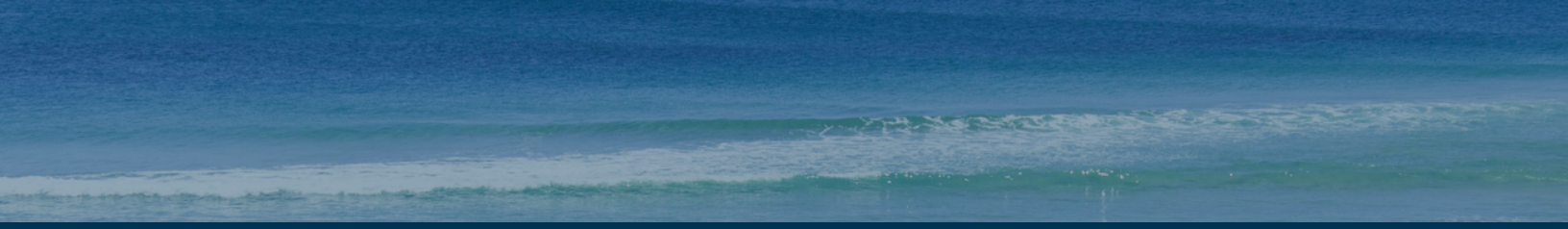
Clean water & human health

Plastic pollution & marine debris

CalCOFI has been used to sample the occurrence of plastic micro-debris in the southern California Current system (Gilfillan et al. 2009, Doyle et al. 2011) and these data have since been used in national and global plastic assessments to provide a regional understanding of microplastic distribution off the West Coast of the USA. For example, at an international level these data are used in an FAO report on microplastics in fisheries and aquaculture and in a global assessment of microplastics in the marine environment from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection. At a national level, the recommended guidelines for sampling methodology presented in the Recommendations for Monitoring Debris Trends in the Marine Environment by NOAAs Marine Debris Monitoring and Assessment Program were heavily influenced by CalCOFI.

Harmful Algal Blooms

CalCOFI has also been cited as a key research and monitoring effort to collect HAB-related data in the offshore area, which is an undersampled region along the California Coast (OST 2016). CalCOFI data have been used to provide environmental context highlighted in scientific summaries of HABs for policy makers (Kudela et al. 2015).



Water quality

CalCOFI research and information has been used to inform water quality assessments, environmental impact assessments, and to monitor compliance for outfalls. CalCOFI collaborates very closely with SCCWRP on water quality related research as well as on regional monitoring through the Central Bight Water Quality Cooperative Program, which is a coordinated monitoring effort of SCCOOS that exists between the Orange County Sanitation District, County Sanitation Districts of Los Angeles County, and the City of Los Angeles. This regionally coordinated survey provides a regional understanding of seasonal patterns in nearshore water column structure and provides context for determining the significance and potential causes of locally observed patterns in the area of wastewater outfalls.

Specifically, CalCOFI data related to salinity (from discharge sites), eutrophication, dissolved oxygen, pH and aragonite saturation state, and status and trends of harmful algal blooms are used in regional water quality assessments.

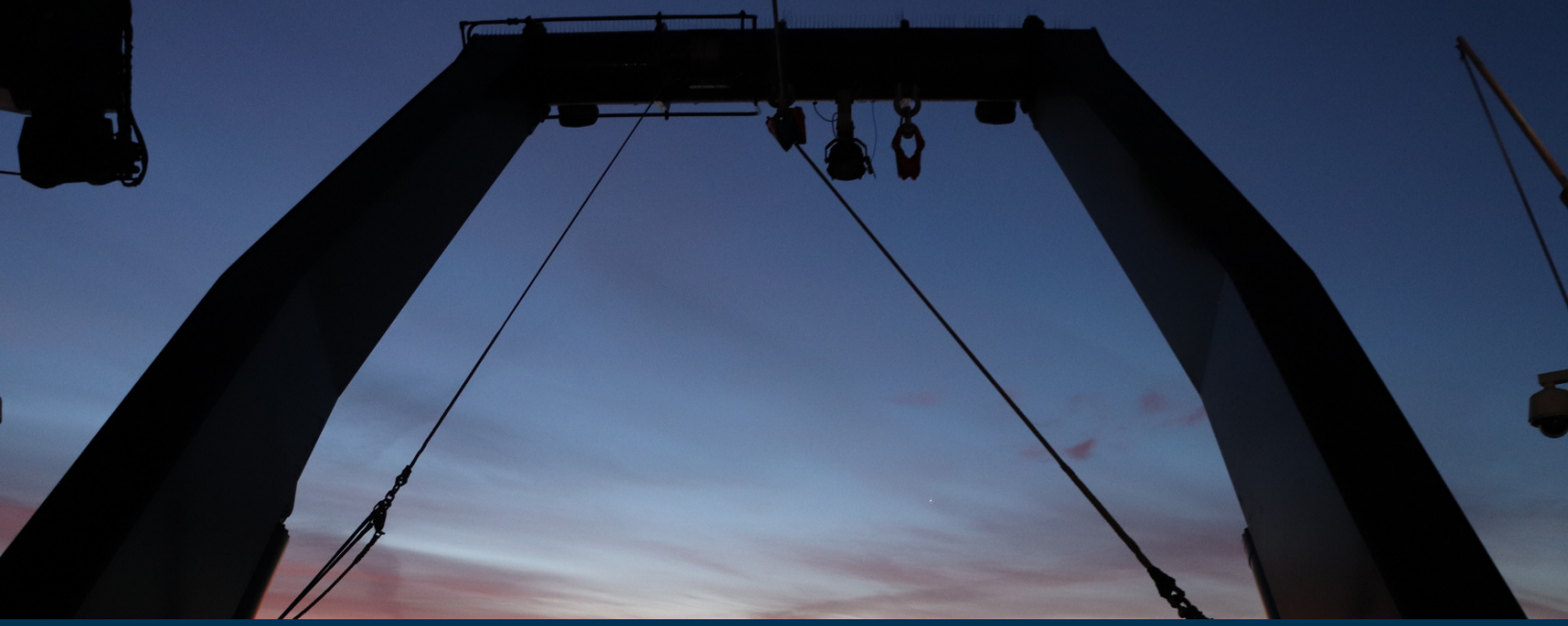
For example, CalCOFI data are used to inform water discharge requirements and permits from the California Regional Water Quality Board and, more generally, assessment reports along the Southern California Coast.

CalCOFI data serves as reference salinity data for which to compare changes over time from outfalls and determine compliance, such as for wastewater discharge requirements from the City of Santa Barbara. The CalCOFI data and reports also inform the City of San Diego's water monitoring and assessment report for local outfalls and applications for outfall renewals.

In addition, CalCOFI reports have been used to inform the contaminants in fish along the California Coast for the Surface Water Ambient Monitoring Program . Also, CalCOFI data have been combined with data from the power plant cooling water intakes to understand the effects of temperature changes from outflows on larval fish along the Southern California coast (Koslow et al. 2015).

Potential Users of CalCOFI for application to clean water and human health

The Regional Water Quality Control Boards, the State Water Resources Control Board, Federal Water Quality Association (part of Environmental Protection Agency, EPA), and CalEPA.



Climate change indicators

CalCOFI also informs our understanding of climate variability, change, and associated stressors on fisheries, aquaculture, renewable energy, human health, and other societal benefits derived from the ocean. Specifically, CalCOFI has been highlighted as a foundational observing program and source of data for California OAH monitoring and assessment. For example, CalCOFI measurements of carbonate system variables to develop proxy relationships for key ocean acidification variables (e.g., omega-aragonite, pCO2) and spatially map regions of high risk of corrosive waters. In addition, CalCOFI information was used in analyses that formed the basis of OA monitoring and research in California and informed the California Ocean Acidification and Hypoxia Science Task Force (2021).

Similarly, the CalCOFI data have been used as indicators of climate change in California. Specifically, the CA Office of the Environmental Health Hazard Assessment (OEHHA) uses the CalCOFI temperature, dissolved oxygen, and copepod data for indicators of climate change (2018).

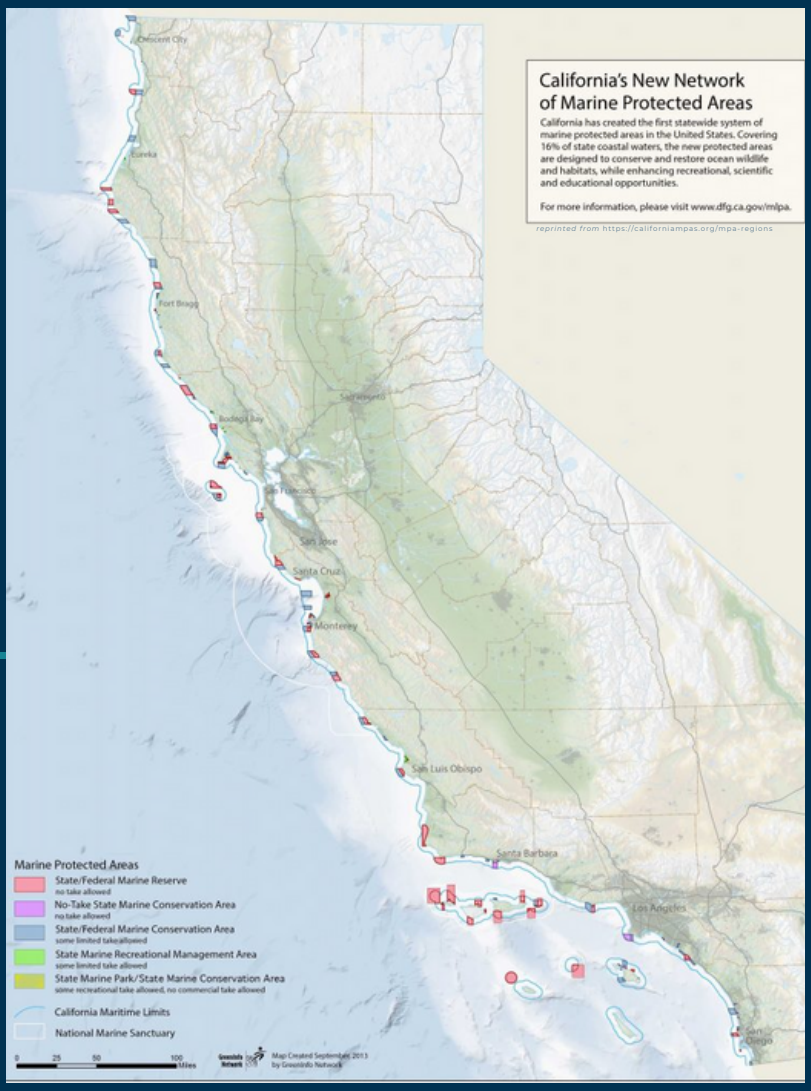
CalCOFI information is also used to help to ready fisheries to climate change by helping to identify changes in ecosystem integrity and support efforts to define ecological tipping points through CalCOFI's annual efforts to characterize the status of the CCS, such as through the CalCOFI State of the California Current Report (Chavez et al. 2017).

Potential Users of CalCOFI for application to climate change indicators

CA Office of the Environmental Health Hazard Assessment (OEHHA), OPC, US Fish and Wildlife Service, and National Marine Sanctuaries.

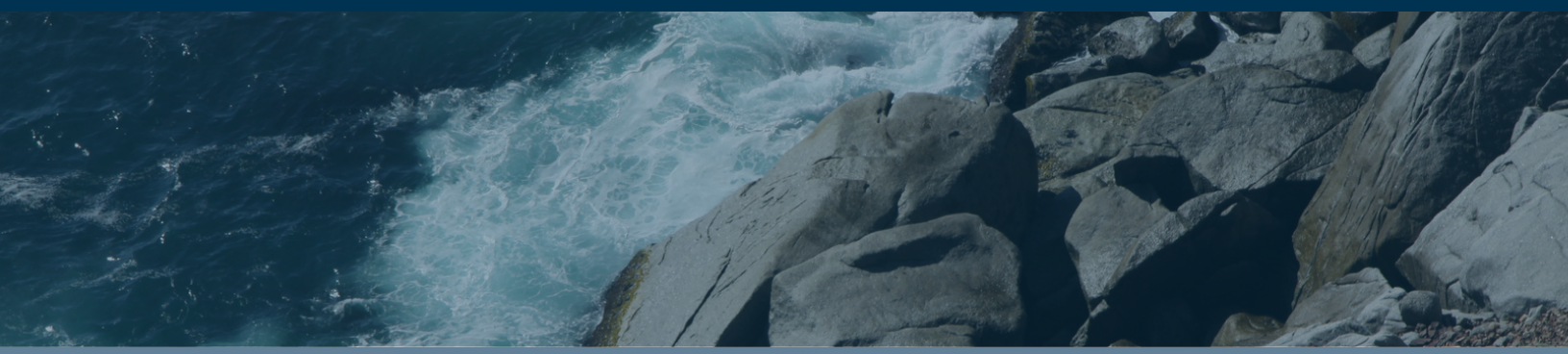
Marine spatial planning

CalCOFI data also support understanding the efficacy of Marine Protected Areas and Conservation Areas and provide essential oceanographic context for which to understand changes over time within MPAs as well as differences among MPA and reference sites. For example, CalCOFI observations have been used to assess rockfish spawning output within versus outside the Cowcod Conservation Areas (CCAs) before and after establishment to better understand their efficacy (Thompson et al. 2017).



Potential Users of CalCOFI for application to marine spatial planning

California Ocean Protection Council (OPC), NOAA, and CDFW.



Nearshore & coastal processes

Much of the CalCOFI data supports understanding the context of nearshore processes, such as those for estuaries and coasts, in relation to the larger scale oceanographic dynamics of the California Current. For example, the Santa Monica Bay National Estuary Program prepared a document detailing a Comprehensive Monitoring Program for the US Environmental Protection Agency (Johnston et al. 2021). This program uses CalCOFI data and indicators, such as the Zooplankton and Ichthyoplankton Community Index, for their ecological condition metrics. In addition, CalCOFI data have been incorporated into the La Jolla Shores Coastal Watershed Management Plan which describes CalCOFI data as providing necessary data on a larger scale for a broader Ecosystem Assessment Framework.

Potential Users of CalCOFI for application to nearshore & coastal processes

National Estuary Program, US EPA, USGS, NPS, and CA State Parks.

Applications to NGOs, foundations, businesses, & observing networks

Non-governmental orgranizations (NGOs)

CalCOFI data are used to support informed decision-making by seafood consumers and businesses to make choices that support healthy oceans. Specifically, Monterey Bay Aquarium's Seafood Watch program evaluates the ecological sustainability of wild-caught and farmed seafood commonly found in the United States marketplace and provides science-based recommendations to the public via a pocket guide and online tool. Seafood Watch uses CalCOFI reports to inform in the White Seabass and California Yellowtail profile. In addition, the National Audubon Society uses CalCOFI for the designation of important bird areas.

Observing networks

CalCOFI is connected to numerous other sectors and users through broader application-based observing networks such as SCCOOS and CenCOOS, as part of the US Integrated Ocean Observing System, and the Marine Biodiversity Observation Network (MBON). CalCOFI will continue to engage with these larger coordinating networks, as well as working toward partnering with NGOs, industry, and foundations to ensure that CalCOFI data is used by a wide range of sectors.

Observe

Highlights 2017-2021

CalCOFI core sampling was successfully carried out on 15 cruises

CalCOFI core sampling has been successfully carried out from 2017-2021 with 15 cruises completed (CalCOFI cruises: 1711SR, 1802SH, 1804SH, 1806SH, 1810SR, 1902RL, 1904RL, 1907BH, 1911OC, 2001RL, 2007RL, 2010SR, 2101RL, 2105SH, 2107SR), and only one canceled due to COVID-19 in May 2020 (2005SH).

CalCOFI variables are highly important to stakeholders

The CalCOFI community indicated that temperature, oxygen, carbonate chemistry and underway pH were all listed in the top ten valued measurements collected by CalCOFI (Engeman et al. 2020).

CalCOFI data have been accessed extensively

The "Available Data" on the CalCOFI website have been accessed on average about 13 times a day, 4,800 times per year, and 52,824 hits since 2010.

CalCOFI hired a Data Manager to help integrate CalCOFI data

In recent years, the CalCOFI program has obtained funds to significantly upgrade its ocean observing capabilities and is working toward the integration of its datasets and development of a web-accessible database. In 2021, CalCOFI hired a Data Manager (in partnership with CCE-LTER) to modernize and further develop the CalCOFI and CCE-LTER data serving capabilities.

CalCOFI partnered with Channel Islands National Marine Sanctuary to develop curated data views

CalCOFI has been in the initial stages of developing curated data views and data synthesis tools to more easily serve and communicate the diverse CalCOFI data streams related to the status and trends of the marine system off the coast of California. At the CalCOFI Conference 2020, the Channel Islands National Marine Sanctuary partners conducted a survey to better understand managers and data users needs. From this, CalCOFI & CINMS have developed an initial concept draft of the potential data serving tool (Figure 6). CalCOFI plans to present the initial, beta version of the visualization tool at the CalCOFI Conference 2021 to get initial community feedback and then refine and finalize the following year.

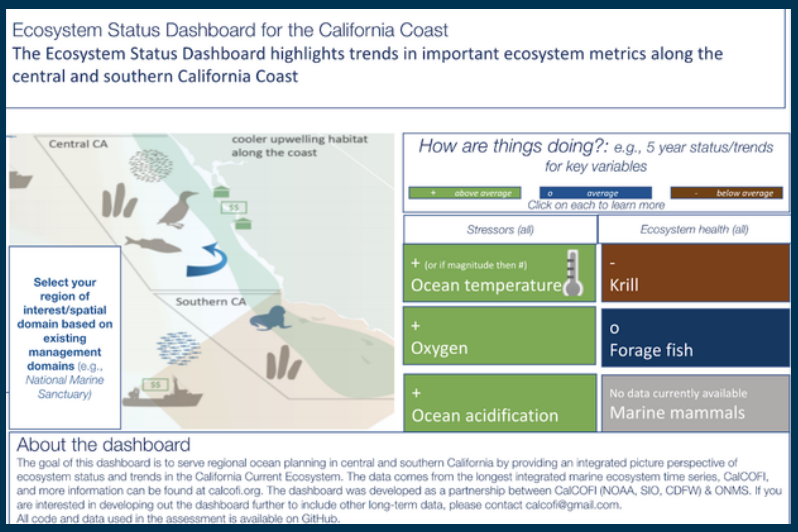
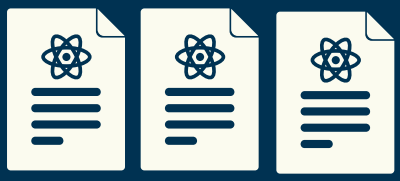


Figure 6. Initial concept for the CalCOFI & Channel Islands National Marine Sanctuary interactive data visualization for marine ecosystem status and trends in the California Current System.

CalCOFI explores augmenting CalCOFI with participatory, citizen science

CalCOFI has been working with a team of early career professionals to begin developing a participatory citizen science application to augment existing ship-based data collection. The team has been conducting surveys to understand ocean users' needs, working with existing citizen science programs, and developing various components of an application that would allow California citizens to collect and upload data on the marine and coastal environments of California.



CalCOFI data used in over 172 individual publications since 2017

The CalCOFI program has facilitated over 172 publications in the past 3 years including: 117 journal articles, 9 books, 2 reports, and 44 theses mentioning or citing CalCOFI (Appendix 4: CalCOFI Publications 2017-2021). In addition, since its inception in 1949, over 10,000 publications have been published as part of the CalCOFI Reports, have used CalCOFI data, or cited CalCOFI.

The State of the California Current Report used CalCOFI data to inform ecosystem-based management

The State of the California Current Report was published annually between 2017 and 2021 (Appendix 4: CalCOFI Publications 2017-2021). The State of the California Current report documents the annual status and trends of physical, chemical, biological, and social indicators in the CCS and is used to inform the California Current Integrated Ecosystem Assessment annual report which is presented to the Pacific Fisheries Management Council.

CalCOFI information used to inform management & policy in the State of California

Knowledge generated from the CalCOFI program has been used to support the management of sustainable fisheries and marine resources; biodiversity and ecosystem assessments; emerging ocean uses such as renewable energy and aquaculture; water quality, pollution, and human health; spatial marine planning; climate variability, change, and associated stressors; and in understanding the broader oceanographic context of nearshore and coastal processes. CalCOFI was mentioned in over 50 online documents from California state agencies from 2017 to 2021, including Fisheries Management Plans, Enhanced Status Reports, Environmental Impact Assessments, Commission Reports, and other policy reports and over 1000 online documents since 1949.

CalCOFI recognized in national & international policy

Since CalCOFI's inception, 32 rules and notices within the Federal Register mention CalCOFI including from the Commerce Department/NOAA, the EPA, and National Science Foundation (NSF) and 17 of those documents have occurred in the past 3 years (2017-2021). At an international level, 3 records mention CalCOFI in the United Nations Library on topics related to climate change, oceans, global ocean science, and ecosystems including from the General Assembly and Programmes. Over 7,010 webpages mention CalCOFI from government websites and over 329 that have been updated in the past 3 years.

Specifically, 1,040 California government webpages (domain: ca.gov) mention CalCOFI and over 61 from the past 3 years, including 964 online documents over all time and 45 online documents in the past 3 years. On the Pacific Fishery Management Council website (www.pcouncil.org) 462 online documents mention CalCOFI, including over 23 that have been updated in the past 3 years, and 43 online documents mention CalCOFI from the North Pacific Fishery Management Council (npfmc.org) with 3 updated in the past 3 years.

Engage

Engage diverse stakeholders and communities

OVERVIEW

A key aspect of CalCOFI is the participatory, collaborative nature of the program, including engagement of researchers, practitioners, and ocean constituents. Specifically, key components of the CalCOFI program are convening CalCOFI events, such as conferences, to bring together researchers and practitioners and assess the needs from various ocean constituents (Appendix 5: CalCOFI Events 2017-2021).

Conferences & workshops

Needs assessments

Outreach

CALCOFI HOSTS ANNUAL CONFERENCES & WORKSHOPS

The annual CalCOFI Conference serves as an invaluable opportunity to bring together the CalCOFI community to share interdisciplinary use-inspired research related to sustainability and resilience in the California Current. The conference is held annually the first week of December and usually consists of a symposium with contributed talks and posters. With the more recent shift to virtual engagement, the CalCOFI conference has slightly evolved to include keynotes, panels, discussion groups and contributed posters.

CALCOFI ASSESSES PROGRAM AND CONSTITUENT NEEDS

A key component of the CalCOFI program is adapting to evolving user needs and evaluating the success of the program. As such, the CalCOFI Coordinator and CalCOFI Committee regularly assess the constituent needs related to long-term ocean observations from local to basin-wide scales through stakeholder engagement during conferences, surveys, and unstructured interviews throughout the year.

CALCOFI CONDUCTS OUTREACH WITH RESEARCHERS, PRACTITIONERS, & CITIZENS

Members of the CalCOFI program, such as the CalCOFI Committee and Coordinator, actively participate in professional events and service to provide continued input, knowledge sharing, and expertise into the CalCOFI program operations. For example, CalCOFI personnel give invited and professional presentations on panels, for keynotes, and at scientific and technical meetings (Appendix 6: CalCOFI Presentations 2017 - 2021).

Engage

Highlights 2017-2021

Over 500 researchers and practitioners from 175 different institutions participated in the 2020 CalCOFI Conference

CalCOFI has hosted 4 conferences on topics relevant to California's marine ecosystems since 2017. For example, 2020 CalCOFI conference, "Understanding unprecedented changes in the California Current", consisted of invited keynotes, invited panel discussions, poster presentations, photo and art submissions, and ten discussion groups on topics relevant to the CalCOFI community.

"This was the best conference I attended this year"

~2020 CalCOFI Conference attendee

The conference brought together 500 diverse stakeholders from 175 institutions (Appendix 7: Institutions affiliated with CalCOFI) from across the California Current, across the Americas, and internationally, to discuss the unprecedented changes in marine and coastal environments of the California Current System.

Based on the feedback survey, participants rated their overall experience as 9/10 and some participants stated that this was, "one of the best CalCOFI conferences I've been to in the last 18 years" and that it was "the best conference I attended this year".

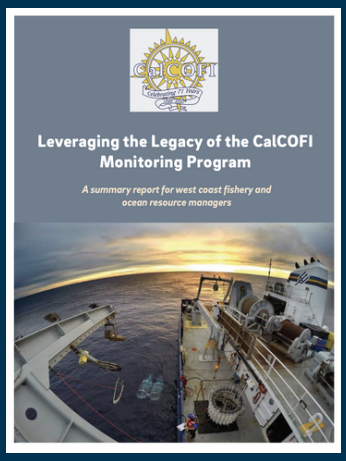
500 people

175 institutions

Over 50 keynote, panel, scientific, policy, and outreach presentations have been given by CalCOFI Committee members since 2017

The CalCOFI committee has been invited to shared research, advice ,and expertise on topics related to long-term observations, climate change, ichthyology, marine resource management, diverse engagement, and ocean sustainability. Presentations have included those at scientific conferences such as the Eastern Pacific Ocean Conference, Larval Fish Conference, Ocean Sciences, Ocean Visions, the American Geophysical Union, and the American Meteorological Society, as well as policy and steering committee meetings such as the U.S. MBON, GOOS, Sanctuaries Advisory Councils, Ocean Protection Council, and the CCIEA Forage meeting (Appendix 6: CalCOFI Presentations 2017 - 2021).

Priorities of the CalCOFI community were published in a stakeholder report in 2020



Stakeholder views and priorities were synthesized and compiled into a report based on the CalCOFI 2019 Stakeholder Workshop and a follow-up survey detailing current and emerging priorities for the CalCOFI program from diverse stakeholder perspectives. The information collected in the questionnaire and summarized in the report has shaped CalCOFI's strategies going forward for monitoring investments, data sharing, and data collection (Engeman et al. 2020). In addition, the outputs from the presentations, community-led discussion groups, and the community of practice that came out of the 2020 CalCOFI Conference helped to inform the vision and objectives of the CalCOFI program. For all key programmatic elements, such as the CalCOFI conference, hackathon, and workshops, the CalCOFI program has conducted pre and post surveys to assess the efficacy of programmatic elements.

Educate

Train the next generation of ocean leaders & citizens

OVERVIEW

The CalCOFI program seeks to share knowledge and communicate with early career professionals, youth, and the community through active engagement, outreach, mentoring, education, and training. Engaging the next generation of ocean and sustainability leaders is essential to bring diverse and innovative viewpoints into research and application and to ensure the sustainability of the CalCOFI program.

The CalCOFI program seeks to engage early career ocean professionals, including undergraduates, graduate students and postgraduates, through the CalCOFI Conference, CalCOFI Hackathon, and research and data science experiences. In addition, CalCOFI engages with educators and conducts public outreach to share the importance of ocean observations, research, marine science, and marine management with California's citizens.

Early Career Ocean Professionals

Youth

Citizens & Community

EARLY CAREER PROFESSIONAL ENGAGEMENT & DEVELOPMENT

Interdisciplinary data and marine science experience through research & data science projects

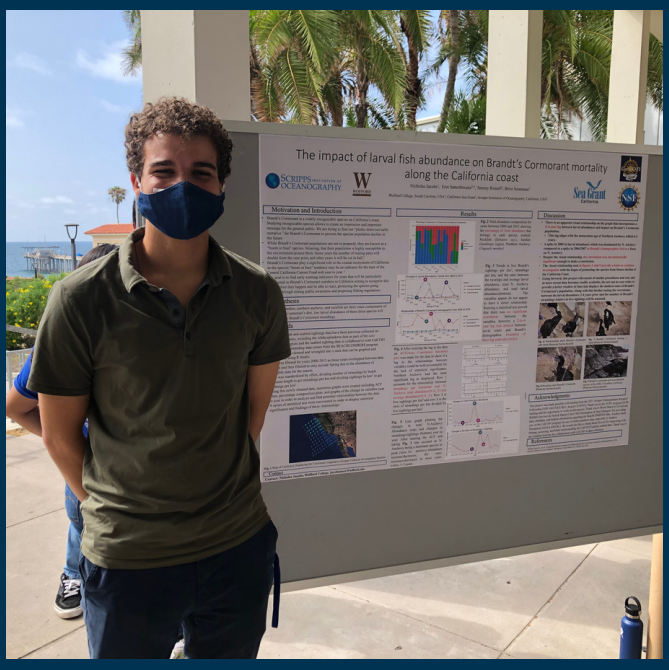
The CalCOFI program provides research, policy, and interdisciplinary experiences that facilitate translating long-term observing data into action. CalCOFI committee members have mentored undergraduate students to postgraduates on independent projects (Appendix 8: Early Career mentees).

For example, CalCOFI works with marine and data science undergraduates within the University of California system, including at UC Santa Barbara (UCSB) and UCSD campuses on data visualization, app development, and research projects using the CalCOFI data. In addition, CalCOFI seeks to promote the inclusion of underrepresented students in research and data science training and mentorship opportunities through existing programs, such as the Summer Undergraduate Research Fellows program.

In addition, CalCOFI committee members mentor data science students as part of their capstone projects and marine science research students, such as in partnership with CCE-LTER through the Research Experiences for Undergraduates (REU) program.

CalCOFI data support graduate student theses & dissertations

The CalCOFI samples, data, and previous CalCOFI publications have been utilized for many graduate student dissertations, such as on topics that include marine ecosystem dynamics including microbial and plankton ecology, deoxygenation, acidification, and nitrogen cycling. For a list of dissertations using CalCOFI data or publications (Appendix 4: CalCOFI Publications 2017-2021).



CalCOFI information used in university seminars, labs, & field courses

The history of the CalCOFI program and CalCOFI data are used in university courses related to oceanography, marine ecology, marine field science, and policy and management. For example, CalCOFI was featured in a lesson plan for introductory interdisciplinary graduate students and upper level undergraduates on, "The Fish, the People, and the Tradeoffs: Social-Ecological Coupling in the Wetfish Fishery of Monterey Bay, California", which was developed as part of a teaching short course. In addition, the CalCOFI samples in the Pelagic Invertebrates Collection (see Open Data & Samples) have been used in over 30 undergraduate and graduate courses at SIO and UCSD. In addition, CalCOFI personnel give guest presentations on topics related to the CalCOFI program in university courses and other classroom settings.

Workshops to understand priorities & needs of Early Career Ocean Professionals

The CalCOFI program seeks to foster diverse and inclusive engagement in research and practice, especially of early career professionals, to ensure the sustainability of the program and cultivate diverse ocean leaders. Members of the CalCOFI team support interactive workshops, large conferences, and other events in order to foster diverse engagement, bring visibility to the CalCOFI program, and to understand constituent and community needs.

Early Career Professional volunteers on the CalCOFI cruises, lab, collections, & events

CalCOFI supports a diverse range of paid and unpaid volunteers on the quarterly cruises, in the lab and collections, and as part of the CalCOFI events. The cruises and lab opportunities provide early career ocean professionals with hands-on experience related to ship-based observations, sampling, and analysis. Volunteers assist with deploying field gear (i.e., CTD-Rosette and plankton nets), sampling and analyzing seawater, and preserving plankton samples. In addition, volunteers assist in the collections and as part of the CalCOFI events to further enhance professional service. The CalCOFI program has had nearly 200 volunteers (Appendix 9: CalCOFI Volunteers).

Science to policy postgraduate experience

CalCOFI provides unique postgrad experiences that link long-term observations to marine resource policy and management. For example, the CalCOFI committee mentors CalCOFI postdocs and California Sea Grant State Fellows on independent research and policy relevant projects related to the CalCOFI program and data.

YOUTH ENGAGEMENT & DEVELOPMENT

CalCOFI data used in K-12 and outreach lesson plans

The history of the CalCOFI program and CalCOFI data are used in data science classes and oceanography within K-12 classrooms. In addition, the CalCOFI program was used in a student workbook by the California Education and the Environment Initiative on ocean currents and natural systems.

CalCOFI archived samples highlighted in educational tours

Historically, the PIC has given tours to hundreds of students, teachers, researchers, and professors on an annual basis, where the CalCOFI time series, its many uses, and value are highlighted. The PIC regularly supports public displays at the Birch Aquarium at Scripps and a number of UCSD lab courses.

CITIZENS & COMMUNITY OUTREACH

Community-based observations & public presentations

Increasingly, CalCOFI has been engaging in public outreach through public engagement and presentations in order to share the value of understanding and managing marine ecosystems (Appendix 6: CalCOFI Presentations 2017 - 2021). CalCOFI has been involved in community-based, participatory research and citizen science. For example, the Hacking for the Ocean student team has been developing a CalCOFI citizen science application. CalCOFI also collaborates closely with outreach organizations such as the Birch Aquarium to provide presentations and interactive lessons related to CalCOFI. CalCOFI has also worked with artists on scientific illustrations related to the CalCOFI collections and program and continues to support efforts to creatively communicate information related to CalCOFI.

CalCOFI on Social Media

CalCOFI has been featured in podcasts and newspaper articles related to the ship operations and research findings (Appendix 11: CalCOFI in the media). The CalCOFI twitter account has over 800 followers and averages about 500 impressions a day, the CalCOFI facebook has over 384 followers, and the CalCOFI instagram account has 383 followers.

CalCOFI website

The CalCOFI website serves as a platform for sharing information and data related to the CalCOFI program and is primarily used by researchers (using data pages), CalCOFI technicians (for referencing methods, cruise dates, specifics for past cruises etc.), students/early career (volunteering page, data pages, methods), and general public/stakeholders (about CalCOFI, history, news). Specifically, the CalCOFI website currently hosts oceanographic data as well as information source/documentation for sampling procedures, cruise dates, conference information, historical information, operations specific to each cruise. The website serves as an archive for oceanographic data, CalCOFI reports, atlases, and peer reviewed publications. The CalCOFI website also provides a source for related communications, including news and updates, and links to the CalCOFI social media accounts. The top visited pages on the CalCOFI website are related to methods and data access and pages on the website average over 3000 visits per year (Appendix 10: CalCOFI website metrics).

Educate

Highlights 2017-2021

53 Early Career Professionals engaged through the 2021 CalCOFI Hackathon

CalCOFI hosted a spring break hackathon to bring together data science, computer science, and marine science undergraduates (41 students) with 12 graduate students and practitioners to work on 10 data science projects using CalCOFI data during the UC spring break.

Based on the feedback survey, students valued the CalCOFI Hackathon because they were able to apply skills to a relevant problem, learn something new, expand their coding skills, network, and learn about CalCOFI. In addition, CalCOFI committee members have served as practitioner mentors for undergraduate and graduate students in the Hacking for the Ocean course (SIOC 209) and following this have provided mentorship for the ongoing development of a CalCOFI citizen science application that facilitates participation of California mariners in the collection of CalCOFI relevant citizen science data.

53

early career professionals

10

data science projects

20+ graduate and undergraduate students mentored on independent projects since 2017

The CalCOFI Committee mentored early career ocean professionals on projects related to dynamics of the California Current System, science to policy interface, marine sustainability, and ocean observations.

Hosted three Interactive Early Career Ocean Professionals workshops

CalCOFI was involved in developing three interactive workshops as part of the annual North Pacific Marine Sciences Organization (PICES) conference and Ocean Visions Summit to provide spaces to bring early career professionals together to share needs and research priorities, in the North Pacific and globally. For example, the CalCOFI Coordinator led the North Pacific Marine Sciences Organization (PICES) Early Career Ocean Professional (ECOP) Workshop with the goal of helping to identify the priorities and needs of Early Career Professionals broadly in the North Pacific and as applied to the California Current System.

CalCOFI reaches 100s of people with outreach presentations

CalCOFI Committee members shared CalCOFI data, research, applications, and history in classrooms throughout California (Appendix 6: CalCOFI Presentations 2017 - 2021)

CalCOFI website revamp in 2021

In 2021, CalCOFI's website was updated to be more user friendly and streamlined. The website features more streamlined and user friendly content.

ORGANIZATIONAL STRUCTURE

The CalCOFI program consists of the core CalCOFI program, which includes the CalCOFI Committee and the CalCOFI technical and data management teams, that are central to the programmatic oversight and operations of CalCOFI. The integrated CalCOFI program consists of the essential contributors and partners of the CalCOFI program who provide advice and strategic vision for the program, along with the collaborative programs (formerly ancillary programs) that provide cruise personnel, data collection, data processing, data analysis, and data management for many chemical and biological parameters (Figure 7; Appendix 12: CalCOFI Personnel)

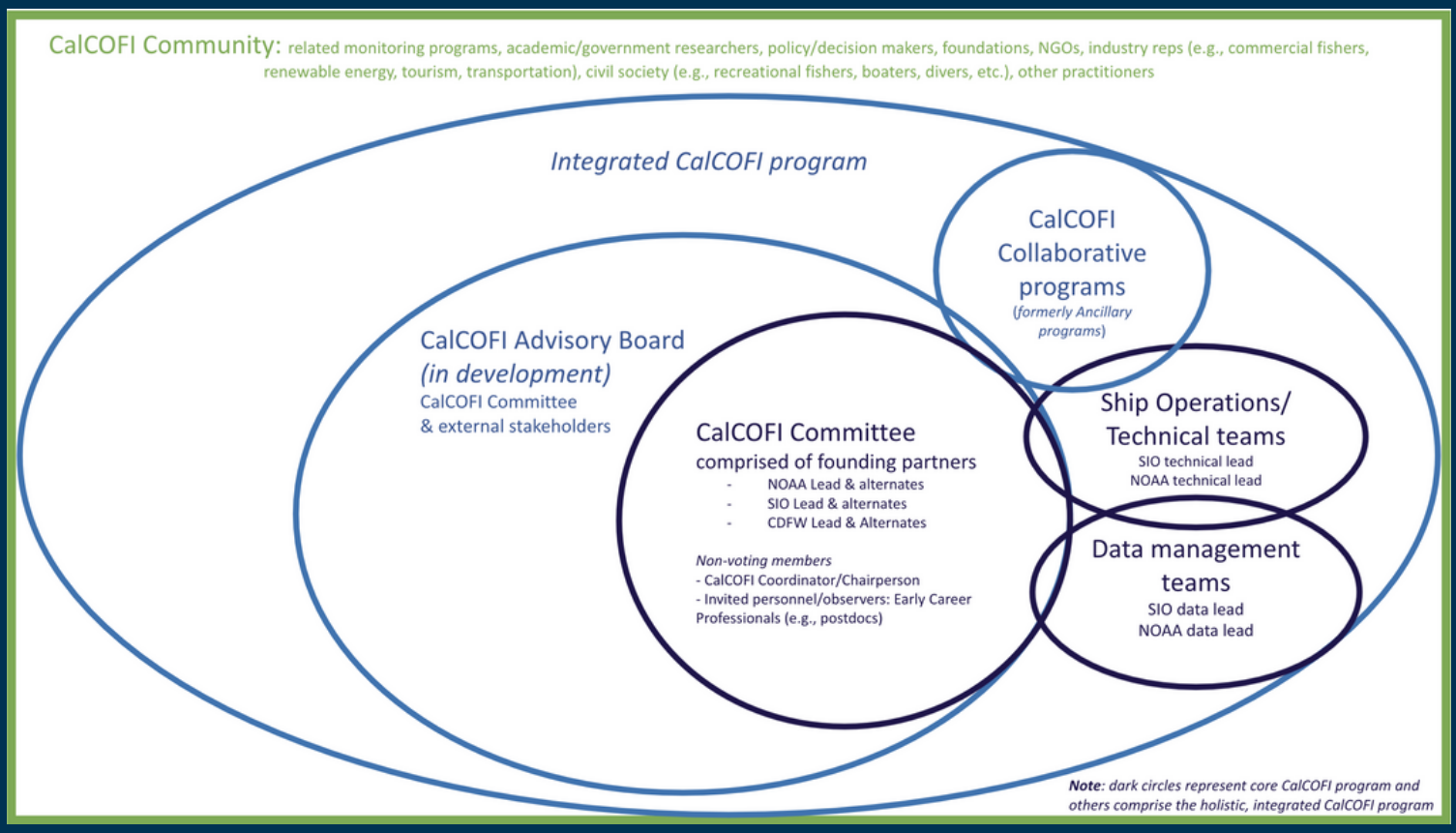
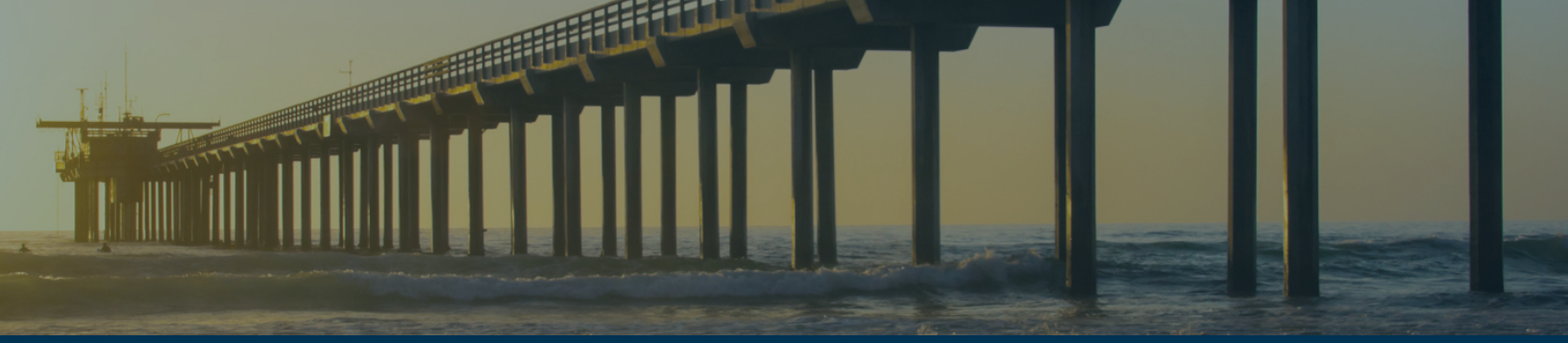


Figure 7. Organizational overview of the CalCOFI program, including the core program (dark purple), integrated program (light blue), and the CalCOFI community (green). The core program is composed of the CalCOFI Committee, the ship operations & technical teams, and the data management teams. The CalCOFI Committee consists of two representatives (lead and alternate) from the founding partner organizations (NOAA, SIO, and CDFW) and the CalCOFI Coordinator as the Committee chairperson. The integrated program consists of the core CalCOFI program with support from the CalCOFI collaborative programs and the advisory board (currently in development). The CalCOFI community broadly consists of all other associated people, observing programs, institutions, and organizations.



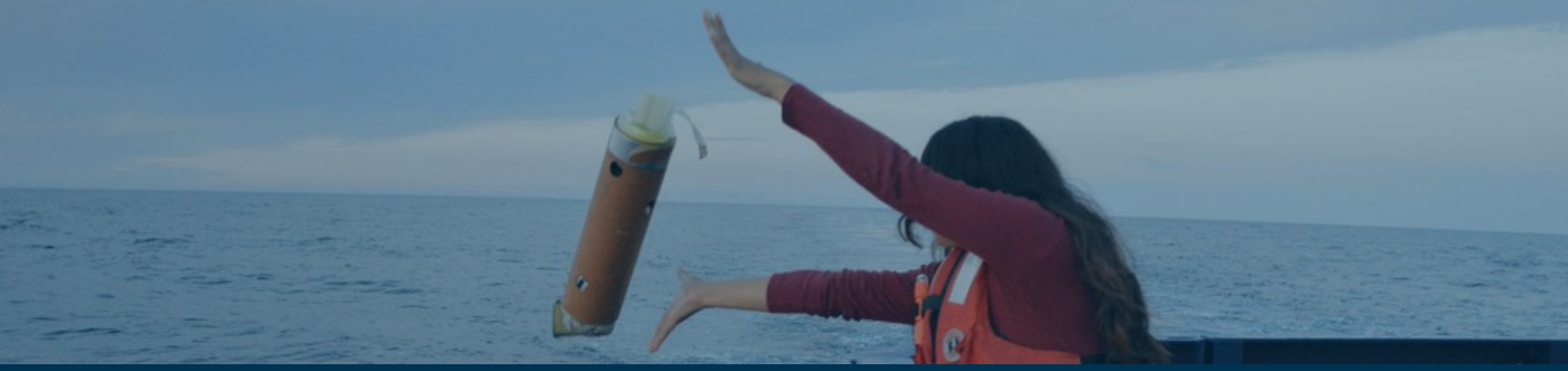
CalCOFI Committee

CalCOFI Committee members

The CalCOFI Committee makes up the main governing body of CalCOFI and consists of the founding partners of the program including SIO (UCSD), the SWFSC (NOAA), and CDFW. There are two representatives (lead and alternates) from each agency that sit on the Committee, including the SIO-CalCOFI Director, the SWFSC-CalCOFI Director, and a representative from CDFW. The basic agreement (memorandum of understanding) among the three agencies that manage the CalCOFI program is renewed every 5 years (current period is June 2019-June 2024). Administrative decisions are cooperatively made by the Committee and scientific decisions are made by the technical team leads and individual Principal Investigators, often with input from the Committee.

Coordination of the CalCOFI Committee

The CalCOFI Coordinator coordinates at least two meetings of the CalCOFI Committee per year, but the Committee often meets much more frequently, often twice per month (24+ meetings per year). The CalCOFI Coordinator develops the CalCOFI Committee meeting agendas, facilitates the meetings, takes minutes, and distributes the meeting minutes with action items in order to inform subsequent meetings and efforts.



CalCOFI Technical & Data management teams

The CalCOFI Technical and data management teams consist of the NOAA Fisheries and SIO CalCOFI Ship Operations/technical teams. The technical teams are responsible for overseeing the data collection and management of the CalCOFI operations and the data management teams are responsible for ensuring that the data are QA/QCed and effectively shared via openly accessible data servers.

The NOAA Fisheries technical team consists of six technicians, two taxonomic identification experts, one data analyst and one data manager. Four of the technicians are responsible for data collection, sampling gear maintenance, sample processing, and data entry, QA/QC, and sharing. Two technicians spend much of their time sorting and removing the fish eggs, larvae, and cephalopods from the CalCOFI net tow samples. Although all members of the technical team have job duties outside of CalCOFI, they also help to manage the extensive larval fish collection.

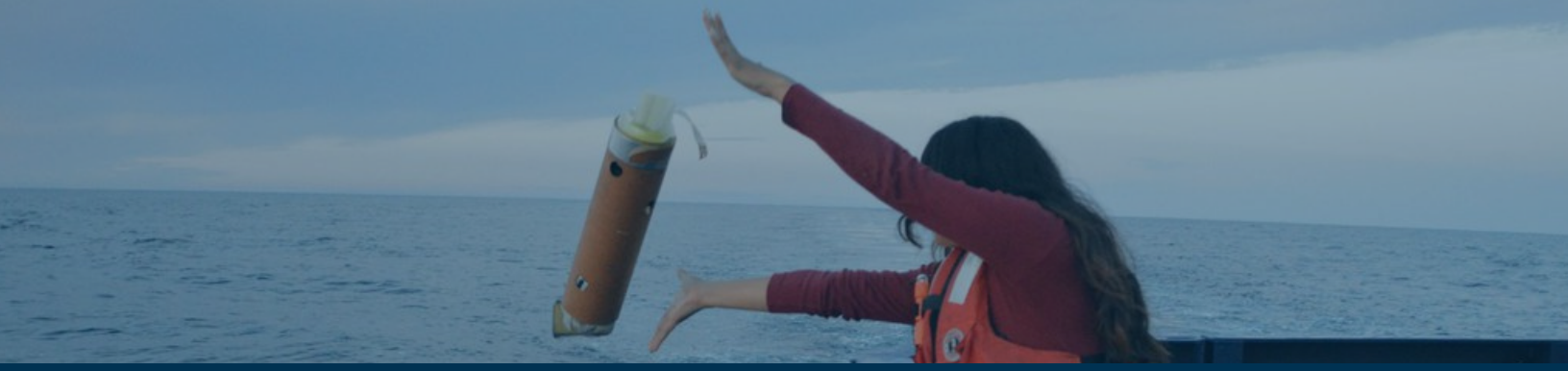
On the SIO side the team is presently composed of five full time technicians charged with the collection, analysis, QA/QC, and data sharing. In addition, the SIO technicians support the volunteer coordination and communications related to the CalCOFI program. CalCOFI also shares one museum collection manager and one data analyst with the collaborative CCE-LTER program, responsible for managing data, curating plankton samples and associated information, and for synthesizing and developing products for data accessing and publishing. SIO also relies on the assistance of student volunteers and assistants that are supervised by the technical team, while simultaneously affording those students with important practical experiences (Appendix 9: CalCOFI Volunteers).

CalCOFI Collaborative Programs

formerly Ancillary programs

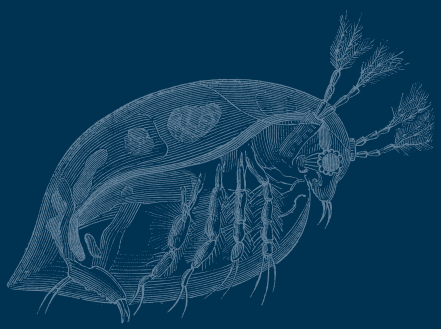
CalCOFI has a strong tradition of collaborating with key partners that both contribute to and leverage CalCOFI, and enhance our understanding of the California Current System far beyond the capabilities of CalCOFI alone.

CalCOFI has leveraged key collaborative programs to meet regional research and management needs. Collaborative programs are of three types: 1) programs utilizing the CalCOFI platform for data/sample collection and/or supporting with the processing, analysis, or management of the samples collected on the CalCOFI cruises, 2) programs that use CalCOFI as a platform to deploy various instruments, and 3) programs that enhance CalCOFIs sampling, research, outreach, and community engagement, such as by increasing the spatial, temporal, or variable/taxonomic resolution of CalCOFI samples, either by sampling along the same transects, or combining data across other long term observing programs.

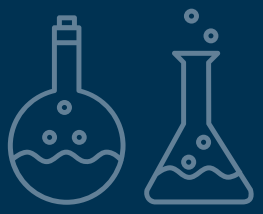


California Current Ecosystem – Long-Term Ecosystem Research (CCE-LTER) program supports biochemistry and lower trophic level sampling

The CCE-LTER program (led by Drs. Mark Ohman and Katherine Barbeau), supported by NSF, has contributed ship time for net sampling on summer and fall SIO CalCOFI cruises, and CCE-LTER has made measurements on CalCOFI cruises since the fall of 2004 to further characterize the biogeochemistry and lower trophic levels of the California Current System, including particulate organic carbon and nitrogen, total organic carbon, HPLC pigments, flow cytometry, size fractionation of chlorophyll, 202 µm net sampling of zooplankton, advanced laser fluorescence, nitrate sensor (SUNA), and pCO2 system. CCE-LTER hosts CalCOFI and CCE-LTER related data for CCE-affiliated PIs through DataZoo. CCE-LTER also conducts process cruises within the CalCOFI grid with the goal of testing specific hypotheses suggested by the CalCOFI dataset and synthesis.



The Martz Lab supports sampling of the inorganic carbon system



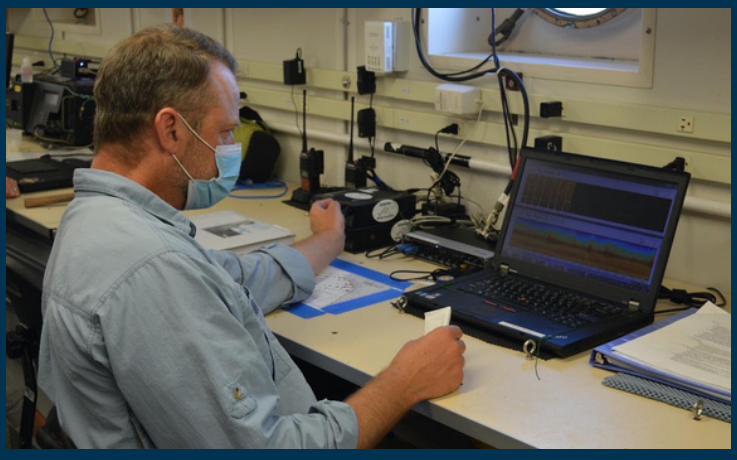
Dr. Todd Martz at SIO supports the technology development as well as the data collection, processing, and analysis of pCO2 and pH measurements aboard CalCOFI cruises with support from CCE-LTER. Currently measurements are carried out using a pCO2/pH underway system built by Todd Martz and bottle samples are taken at selected stations for the analysis of TCO2, TAlk and pH (previously collected by Dr. Andrew Dickson at SIO).

California Sea Grant supports translational research, program coordination, education, and outreach

California Sea Grant entered a partnership with CalCOFI in 2020, and supports CalCOFI's research and education, outreach, and engagement through the Sea Grant Marine Ecology Research and Extension Specialist and CalCOFI Program Coordinator position. The Research and Extension Specialist and Program Coordinator works with agencies, nonprofit organizations, local businesses, and members of the California coastal community to identify emerging marine resource problems and opportunities, conduct applied scientific research, and share findings with key stakeholders and the community.

Southern California Coastal Ocean Observing System (SCCOOS) supports coastal data collection, management, and visualization

The Southern California Coastal Ocean Observing System (SCCOOS), a regional node of the US Integrated Ocean Observing System (IOOS), provided support to extend the standard CalCOFI station pattern inshore for 9 additional stations on each survey, which has since been integrated into the Core CalCOFI program. At each of these approximately 20 meter deep stations, a CTD and Bongo net are deployed to collect data valuable for monitoring the nearshore environments of coastal California. These coastal stations enhance our knowledge of the nearshore fauna as well as the connectivity between nearshore and offshore marine habitats. Data available to date indicate that the original CalCOFI nearshore stations and more coastal SCCOOS stations sample a similar oceanographic environment. Today, SCCOOS supports the management and visualization of CalCOFI data through useful data products.



Scripps Whale Acoustics Lab supports marine mammal observations

Since April 2004, the Scripps Whale Acoustics Lab at SIO (Drs. John Hildebrand and Simone Baumann Pickering) has added a visual and acoustic marine mammal survey component to the CalCOFI program to study cetacean ecology and habitat with support from the U.S. Navy. By integrating CalCOFI environmental and cetacean data, the Scripps Whale Acoustics Lab develops ecological models for cetacean habitat in the region offshore of southern California to improve our understanding of the role of cetaceans in the California Current System and assist with Navy operations.

Farallon Institute supports seabird observations

The Farallon Institute (Dr. Bill Sydeman) supports seabird observations on each spring, summer, and winter CalCOFI cruise to better understand seabird distribution and abundance in the California Current. These data are coupled with hydrographic and plankton data that are collected concurrently by the ship during survey transects, which provides researchers a snapshot of ecosystem conditions and biological community structure across several trophic levels.

The NOAA-CalCOFI Ocean Genomics (NCOG) program in partnership with J. Craig Venter Institute (JCVI) supports genomic sampling and analysis

The NCOG program began in 2014 and was originally funded by NOAA Fisheries and OAR in partnership with the J. Craig Venter Institute (JCVI) and Dr. Andrew Allen. Despite cuts to these funds, the CalCOFI program remains committed to collecting and processing genomic samples. The program's original objective was to assay the diversity and distribution of microbes and other plankton. The ability to link analyses of microbial community structure and diversity directly to measurements of ecosystem indicators (e.g. productivity) will enable evaluation and prediction of microbial population and community dynamics. Thus, high-throughput DNA and RNA sequencing complements and augments oceanographic, biological, and biogeochemical observations in CalCOFI (e.g., Taylor et al. 2015, Venrick 2015). To date, conserved markers 16S and 18S have been amplified and sequenced from samples spanning all seasons, stations and depths during the 2014-2019 CalCOFI cruises.

The Venrick Lab contributes to phytoplankton sampling

CalCOFI has provided samples of preserved phytoplankton to Dr. Elizabeth Venrick who enumerates the larger phytoplankton using inverted microscopy to delineate community structure and associated changes over space and time.

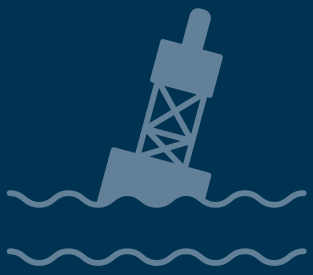
The Terrill Lab contributes to CalCOFI ship operations and student employment opportunities

The Terrill Lab provides ship days for the CalCOFI program and the CalCOFI technicians help to deploy mini wave buoys on most CalCOFI cruises. The Terrill Lab also supported three undergraduate students to further develop a citizen science data collection application to enhance the spatial and temporal coverage of CalCOFI sampling through participatory citizen science (see Educate).

The Channel Islands National Marine Sanctuary supports the communication of CalCOFI data

CINMS and CalCOFI have developed a partnership to develop curated data views, data visualizations, and other communication tools in order to translate the CalCOFI data into a user-friendly, accessible, and visually appealing format. Specifically, CINMS and CalCOFI have provided support for a contractor to develop a data visualization tool to visualize information on the state of the California Current updated on a quarterly or annual basis.

CalCOFI deploys moorings, drifters, buoys, and other instruments for partnering programs and supports with short-term and pilot projects



CalCOFI serves as a valuable platform to deploy various oceanographic and other instruments for research and outreach. For example, the CalCOFI program has deployed Apex profiling floats for the Navy, surface drifters for the Global Drifter Program, and weather balloons and other instrumentation for measuring and sampling aerosols for researchers at SIO. In addition, the CalCOFI program has also deployed buoys for the Radio Club at Mount Carmel High School for outreach.

The CalCOFI sampling grid/geometry is used by other programs in order to compare and calibrate data

The California Underwater Network samples along three of the CalCOFI lines (Lines 90, 80 and 66.7) and uses the CalCOFI data to calibrate their sensors. In addition, CalCOFI measurements at the sites of the CCE1 and CCE2 moorings provide calibration data for the moorings' sensors. The MBARI Studies of Ecological and Chemical Responses to Environmental Trends (SECRET) has sampled off of line 66.7. In addition, NOAA's West Coast Ocean Acidification (WCOA) cruise samples line 90, 80, and 73.3. Finally, other long-term programs, such as IMECOCAL, maintain sampling on historic CalCOFI sampling locations.

The CalCOFI program also enables shorter term, pilot projects

Testing out equipment, methods and questions in pilot studies increases the likelihood of bringing in new funding and partnerships. A recent example was part one of a two part atmospheric pilot study by Prather Lab at SIO on the summer cruise of 2021. Here instrumentation for counting, sizing and sampling aerosols were installed on the R/V Sally Ride. On the fall cruise 2 students/researchers will participate in the cruise and carry out additional sampling of aerosols, the ocean surface micro layer and test out new instruments. If successful, this pilot study will create the foundation for securing funding and implementing a future ocean-atmosphere collaborative CalCOFI program.

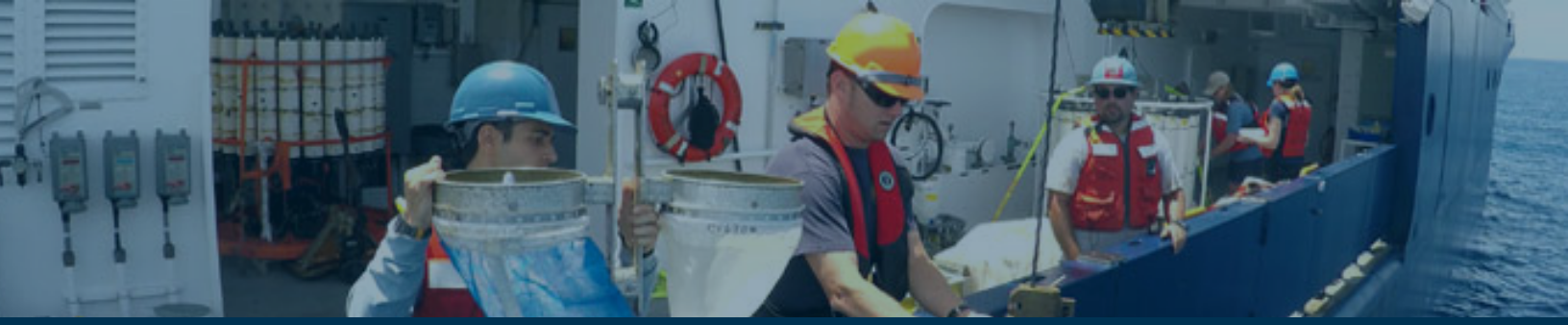
CalCOFI Advisory Board

in development

The CalCOFI Advisory Board is in the process of being established and will serve as a scientific steering committee and advisory body to the CalCOFI Committee. The CalCOFI Committee will establish and maintain the membership of the Advisory Board and the CalCOFI Coordinator will coordinate implementation of all Advisory Board activities.

The Advisory Board will consist of 6 - 12 representatives from the collaborative programs, State and Federal government, academia, and ocean constituents, such as commercial and recreational users, and conservation groups. The Advisory Board members, will participate in two board meetings per year, at least one of which will be held during the annual CalCOFI meeting and serve for a period of three years, with potential for reappointment. Advisory Board members may be replaced during the 3-year period if the member is no longer able to serve in the required capacity.

Advisory Board members will provide feedback and guidance on proposed annual research and monitoring objectives, review summaries of annual expenses, and participate in committees with targeted objectives that support the CalCOFI mission and associated activities (e.g., student scholarships, funding opportunities, education and outreach).



CalCOFI Community

The CalCOFI community is a diverse network of stakeholders within various local, state, federal, and international organizations, who come together to share information, exchange ideas, and develop priorities for long-term monitoring to support ecosystem-based and marine resource management and resilience in the California Current. CalCOFI works to convene and partner with a diversity of stakeholders across the entire observing value cycle to create shared value and build trust. The CalCOFI community includes diverse partners from local to international scales and across sectors (Figure 8). For example, through the CalCOFI Conference and Workshop, CalCOFI fosters and convenes a diverse community of researchers, practitioners, stakeholders seeking to understand long-term changes in the California Current and identify shared priority areas for research, monitoring, assessment, and management (see Collaborative Programs). CalCOFI's communications platform (MailChimp) includes 754 subscribed users.

According to the 2020 CalCOFI Conference survey, the CalCOFI community consists of individuals from 23 different California universities, including 7 of the 10 University of California schools; 19 state and local government agencies in California, including Ocean Protection Council, Ocean Science Trust, Southern California Coastal Water Research Project, and the City of San Diego; 2 West Coast universities and 3 state agencies from Oregon and Washington; 5 West Coast Tribes, 16 universities in the United States, 30 Federal agencies including those from NOAA's line offices, BOEM, Navy, National Parks Service, and the Pacific Fisheries Management Council; 35 international universities and organizations including from Mexico, Latin America, and Oceania; 22 non-governmental organizations and foundations; 9 businesses including from fisheries, aquaculture, sustainable building, scientific instruments, and consulting; and 6 outreach organizations including aquariums, libraries, schools, and natural history museums (Appendix 7: Institutions affiliated with CalCOFI).

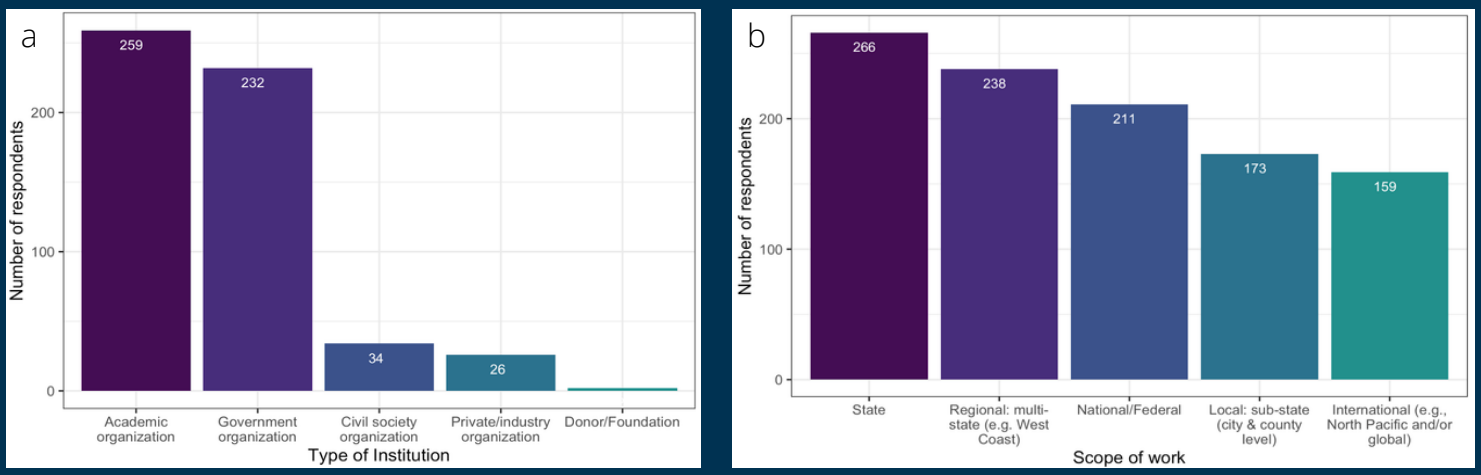


Figure 8. CalCOFI Community composition (n = 513) related to sector of organization (a) and geographic scope of work (b) from the CalCOFI 2020 Conference survey. The CalCOFI Community consists of mostly academics & government professionals with some professionals from civil society, private/industry organizations, and foundations. The CalCOFI Community is comprised of professionals with work mainly at the state, West Coast, Federal with some local and international institutions.

Financial & Operational Support

The CalCOFI program is supported by recurring support, opportunistic grants, and collaborative programs (Appendix 13: CalCOFI Funding 2017-2021).

Recurring Support. CalCOFI is principally supported by annually recurring funds that cover ship operations and data collection, data management and curation, and the CalCOFI technical group personnel. Annual funds from SWFSC via CIMEC/CIMEAS ($1.8 million) have remained at the same level for the past decade, despite marked increases in program costs. For the past 4 years, the growing funding shortfall has been mitigated by 10 days of ship time from the Office of Naval Research, awarded annually to the Terrill Lab for collaborative research. Additionally, the CCE-LTER program provides 6 days of ship time annually. Beyond ship operations, SIO, SWFSC, CDFW and CASG contribute equally ($30k annually) to support the CalCOFI Coordinator position, a full-time CASG Extension Specialist (currently, Dr. Erin Satterthwaite). SCCOOS provides technical support for data synthesis and applications ($70k annually). Finally, the SIO Director's Office provides $5k annually for required supplies that are disallowed on NOAA funds.

Fixed, one time, or opportunistic grants. CalCOFI personnel regularly apply for and sometimes receive non-recurring grants to support or augment the program. For instance, the CalCOFI SIO Director (currently, Dr. Brice Semmens) and Dr. Mike Landry were awarded an NSF RAPID grant to use the CalCOFI platform to investigate the mechanistic underpinnings of the unprecedented Northern Anchovy boom occurring in the CCE, despite record warm water temperatures.

In addition, Dr. Brice Semmens was provided $500,000 in discretionary funds at the start of his CalCOFI Directorship. These funds have been used to address funding gaps associated with CalCOFI operations and funding needs arising outside the scope of regular governmental grants. For instance, discretionary funds have been used to support the hiring of the CalCOFI coordinator, to purchase equipment (e.g., vehicles for the program), and will support ongoing and evolving personnel costs and overages associated with the Data Analyst and CalCOFI Coordinator position.

CHALLENGES, OPPORTUNTIES, & FUTURE DIRECTIONS

This section highlights the challenges, opportunities, and the future directions of CalCOFI. Specifically, this section explores where the CalCOFI program is heading in the coming years and what the program plans to focus on to be effective at achieving CalCOFI's vision, mission, and goals.

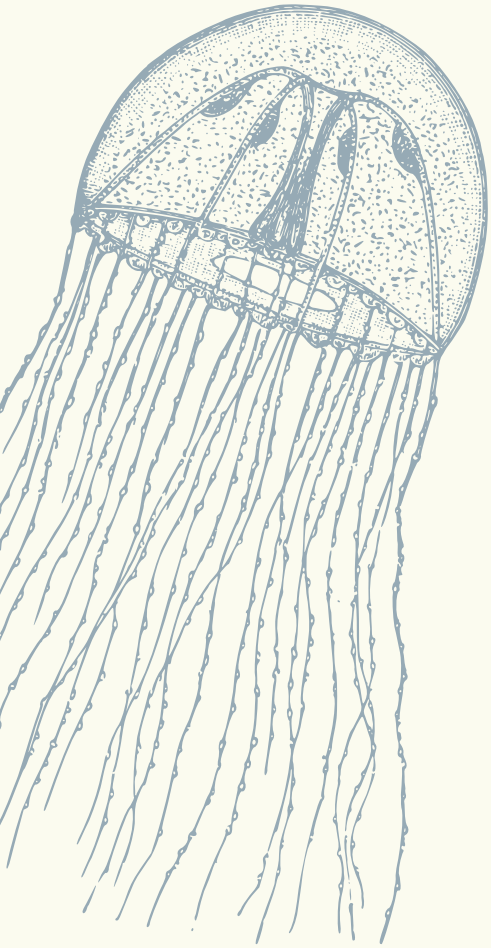
- Expand support for core ship operations, data processing, analysis, management, and curation through existing and expanded partnerships.

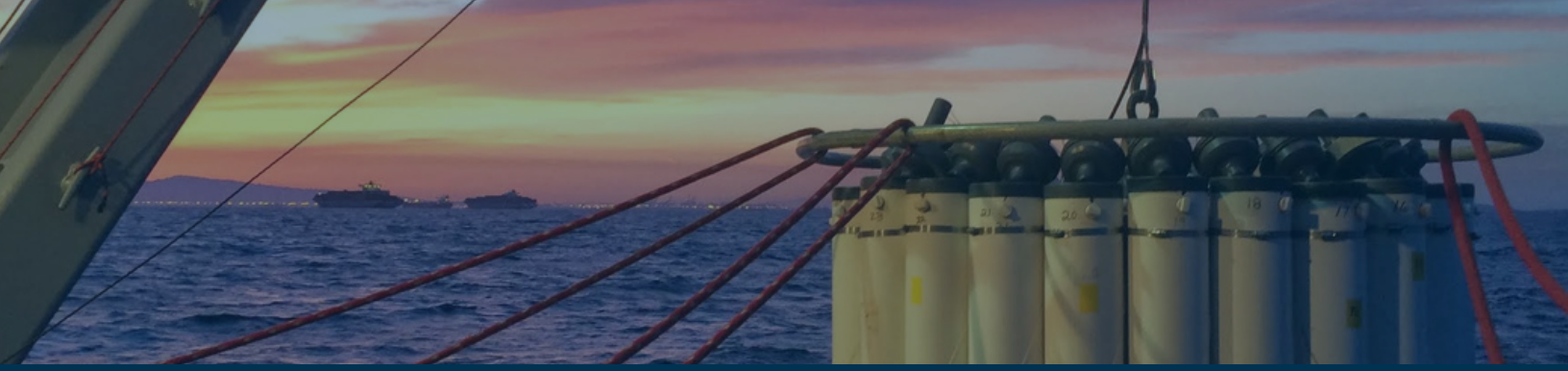
-Augment existing sampling with AUVs, UxS, and other emerging technologies to enhance resolution and ensure sustainability of the program.

-Ensure relevance from local to international levels from research to application through stakeholder and community engagement

-Integrate direct societal connections and applications to CalCOFI through citizen science, and social data/indicators

-Foster education, outreach and diverse community engagement through research and data science experiences, lessons, and creative communication





Expand support for core ship operations, data processing, analysis, management, and curation through existing and expanded partnerships

Core ship operations. At present, the allocated CalCOFI core budget covers approximately half of the needed ship time to carry-out "business as usual" CalCOFI sampling in the Summer and Fall (SIO operations), and with the recent 50% increase in daily cost, ship time has become increasingly hard to support. In previous years, the additional CalCOFI ship-days were supported by ONR (10 days) and by NSF through the CCE-LTER program (6 days). We do not expect this ONR funding to continue indefinitely, and thus foresee a major budget shortfall in the coming years.

We note that as CalCOFI has expanded northward, originally with the expansion of the Pacific sardine population, SIO CalCOFI has had to expand its data processing and archival activities with no increase in resources. In addition, the increasing costs of salaries and ship use (fuel, especially), have not been accompanied by a commensurate increase in funding. There is no easy way for CalCOFI to meet all its obligations in the current funding environment. Nevertheless, CalCOFI will continue to work with NOAA and CDFW to seek the means to do so, through development of collaborative programs leveraged off the CalCOFI platform and continued pursuit of additional funding sources, including ONR. This may include continuing to diversify funding sources that are part of the core CalCOFI program and working toward line item funding.

In moving forward, the CalCOFI program needs a "fit for purpose" vessel to carry out the CalCOFI cruises and standard operations in the Summer and Fall. This could be a new UNOLS regional class ship similar to the retired RV New Horizon in size and berthing space (between the RV Sally Ride and Sproul), or, CalCOFI could move operations to private contract vessels. The berthing space needs to accommodate all technicians and ship operations staff, early career professionals, personnel from the occasional pilot program, as well as space for new additional longer term program personnel. We will also continue to explore options for AUV/drone data collection as an augmentation and when the technology makes it possible, a replacement, for some aspects of shipborne science (e.g., the ISIS data collected by NWFSC/OSU).

The current plan for 2022 cruises is to use R/V Sally Ride for the summer CalCOFI cruise and to charter the R/V Bold Horizon for the fall CalCOFI cruise because we do not have enough funds to use R/V Sally Ride for more than one cruise within one funding cycle. The charter option is not a permanent solution, and we are actively pursuing a more sustainable option.

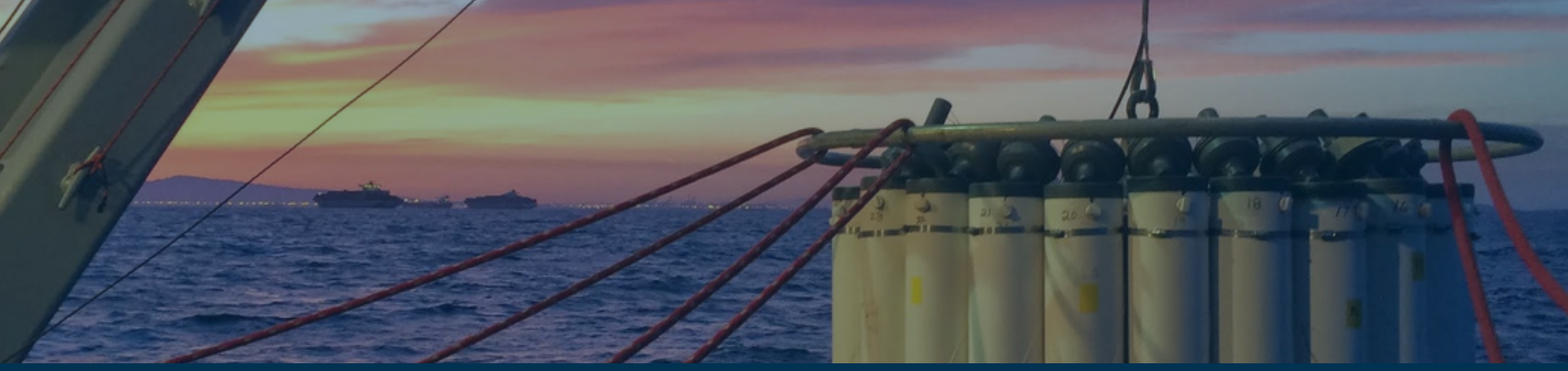
We are currently in negotiations to expand the NOAA component of the CalCOFI partnership by collaborating with NOAA National Ocean Service (NOS) Office of National Marine Sanctuaries (ONMS).

The heart of the CalCOFI mission lies in ecosystem monitoring which is well-aligned with the ONMS mission to protect treasured places in the ocean (and Great Lakes) by conducting and supporting monitoring programs tailored to the information needs of each sanctuary. The Channel Islands National Marine Sanctuary (CINMS) relies on CalCOFI data collected in and around the CINMS for their Condition Report and has a keen interest in working with CalCOFI to expand our monitoring to more sites within the CINMS. We are also expanding this negotiation to include the Monterey Bay National Marine Sanctuary (MBNMS) because they also rely on CalCOFI data collected in their sanctuary and want us to increase the frequency with which those sites are sampled (i.e. from twice annually, to three times a year). Together CINMS and MBNMS, under the ONMS umbrella, are able to partner with NMFS to request additional NOAA research vessel days to support an expanded fall CalCOFI cruise, carried out in full on NOAA vessels, to sample the core pattern plus the lines/stations north of Point Conception up to San Francisco (previously only occupied in the Winter and Spring). These additional NOAA sea days, if granted, would come at no additional cost to our program, and would thus allow us to use a portion of annual NMFS/CIMEAS funds to validate, calibrate and implement emerging monitoring tools (e.g. autonomous vehicles, eDNA samplers, imagine/AI methods).

Data collection, processing, analysis, management, and curation. At present, many physical, chemical, and biological parameters are collected using the CalCOFI platform, yet many of the parameters are processed, analyzed, curated, and managed by partner programs.

The oceanographic and ichthyoplankton data have dedicated NMFS technicians to support the processing, analyses, curation, and management of the data. However, some sample streams (e.g., Manta net samples) are delayed or not enumerated due to chronic short staffing of expert taxonomists or acute staffing and facility access issues related to the pandemic.

The main bottleneck for the ichthyoplankton samples is the sorting process. Twenty-five years ago, SWFSC had a team of five dedicated sorters who were able to keep pace with the collection of all net tow samples collected during each cruise. In recent years SWFSC has had two sorters who have duties in addition to sorting. This chronic reduction in ichthyoplankton sorting staff has required prioritization of the formalin-preserved bongos and shelving of the unsorted ethanol-preserved bongo, Manta, and Pairovet samples. Although we don't have staff time to devote to sorting these samples at present, we do not have plans to eliminate these net tow collections. Most other parameters do not have dedicated resources to support the data collection, processing, analyses, curation, and management, so these functions reside in collaborative programs (e.g., inorganic carbon, phytoplankton, holozooplankton, seabirds, marine mammals) or currently do not exist (e.g., merozooplankton/invertebrate larvae). Thus, expanding support for the processing, analyses, curation and management of merozooplankton/invertebrate larvae, eDNA, and atmospheric sampling components of the program would be fruitful, as well as working to bring the data streams that are currently part of the collaborative programs into the core CalCOFI program.



Recommendations

Expand support for core ship operations, data processing, analysis, management, and curation through existing and expanded partnerships

1) Hiring a merozooplankton specialist to enumerate invertebrate larvae by station from all samples (past and present). Larval invertebrates would be especially important to enumerate since they comprise many state-managed species so this could be envisioned as a Scientific Aid Position for enumerating larvae in partnership with CDFW;

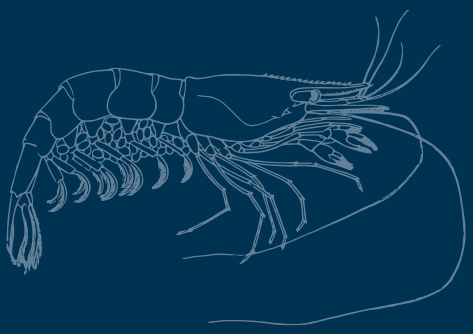
2) Hiring an eDNA curator to manage and curate the eDNA samples, and expanding our eDNA sampling capabilities by acquiring a larger CTD rosette with space for an in situ eDNA water column sampler;

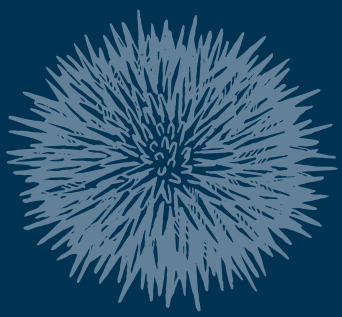
3) Metabarcoding ethanol samples to develop a zooplankton eDNA timeseries from ethanol preserved bongo specimens and sequencing to develop a reference library;

4) Adding atmospheric sampling to existing ocean sampling via aerosols;

5) Continuing Compound Specific Isotopic Analysis of Amino Acid 15N isotopes work on larval anchovy and sardine that has proved very useful for stock assessment and forecasting, and continue to explore its use for other sampled species, and

6) Acquiring a new CTD rosette with space for an eDNA sampler.





Augment existing sampling with AUVs, UxS, and other emerging technologies to enhance resolution and ensure sustainability of the program.

As mentioned above, the challenges of ship-based observations will need to be partially addressed by continuing to incorporate new technologies (e.g., imaging, eDNA, OA, fine scale glider video, compound specific stable isotope analyses) into core CalCOFI collections to maintain the current level of sampling as well as to expand the spatial, temporal, and parameters sampled as part of the CalCOFI program. At present, there are insufficient technologies to collect biological samples that would parallel the existing biological specimens and data collected on the CalCOFI cruises (although promising existing efforts include ZooGliders, FloCytobots, and eDNA sensors).

In addition, because of CalCOFI's uniquely broad and long set of physical samples (both chemical and biological) the program is uniquely suited to validate, calibrate, and integrate uncrewed systems, while developing sufficient overlap between the novel technologies and traditional ship-based sampling to ensure that the continuity of the time series is maintained. As new technologies emerge, it will be critical to continue to have preserved specimens for future analyses, since it is invaluable to have samples that can be analyzed with future technologies. This has been well demonstrated by recent work involving eDNA and compound specific stable isotope analysis. As climate change alters populations and leads to northward range shifts, expanding CalCOFI further north, likely with non-ship based sampling platforms, will be a vital next step.

Ensure relevance from local to international levels from research to application through stakeholder and community engagement

The sustainability of CalCOFI hinges upon connecting the long-term data and information to users, especially with the State of California, the United States, and more broadly the North Pacific and internationally. CalCOFI is relevant to a range of research and policy questions, related to natural resource management, ecosystems, biodiversity and conservation, water quality, among many others.

Stakeholder engagement. The CalCOFI data streams need to continue to be used for policy, management, and other relevant applications. Specifically, CalCOFI will continue to work with state and federal natural resource managers and supply data to inform stock assessments and ecosystem-based fisheries management. In addition, efforts could expand to build more indices based on larvae of state-managed species and use them in assessments and management strategy evaluations (MSEs). The phytoplankton species enumeration that had previously been conducted by CalCOFI could be reinstated to support ecosystem analysis and harmful algal bloom (HAB) understanding and monitoring. CalCOFI data will also be used to understand how climate change stressors, such as ocean acidification, hypoxia, and heatwaves correlate with biological assemblage composition using the stations that have historic data on carbon chemistry.

In addition, CalCOFI can enable research to understand the effects of offshore renewables, aquaculture, and other offshore infrastructure on the marine ecosystem. CalCOFI data will continue to be applied to offshore-nearshore coupling, connecting nearshore and coastal patterns with larger scale oceanographic processes to better contextualize changes off of California. CalCOFI will also continue to engage in national observing efforts and networks (e.g., MBON, OOSes) as well as international programs like Marine Life 2030 (Ocean Decade endorsed program) to maintain connectivity and relevance at international scales. Also, CalCOFI will continue to engage policy makers and state legislators, potentially through a science and policy mentorship program, in order to develop a robust and sustained relationship with Capitol Hill and Sacramento lawmakers.

Data products and communication tools. To facilitate the use and dissemination of the CalCOFI data, the CalCOFI program will continue to work toward developing CalCOFI data access and use trainings, developing relevant data products and visualizations catered to specific audiences, and engaging early career professionals in the collection and use of the CalCOFI data.

Foster education, outreach and diverse community engagement through research and data science experiences, lessons, and creative communication

Early Career Ocean Professionals (Undergraduate – Early Career)

CalCOFI will continue to engage, train, and highlight the achievements of Early Career Ocean Professionals (ECOPs) through the annual conference and workshops, research and cruise experiences, and data science and other educational experiences. At the CalCOFI Conference, CalCOFI will work to integrate opportunities to highlight early career professional achievements, such as through presentation awards, and to continue to foster a network of early career professionals along the West coast, such as through student-led aspects of conference programming as well as socials. In addition, CalCOFI would like to expand the at-sea experience for ECOPs by incorporating undergraduate and possibly graduate students as regular participants on the cruises. This would provide a steady, reliable supply of helpers while providing more practical at-sea experience and skillsets to students while still earning credit toward their degrees or as a graduate student training opportunity. This could also take the form of a formal "practical oceanography" course offering that includes the CalCOFI cruise as a field part, teaching the students, with the assistance of the CalCOFI technicians, how to run a cruise and the different types of samplings, at sea and later ashore based analysis, QA/QC and result interpretations.

Since the cruise schedule is predictable well in advance, it may be easy to have the CalCOFI cruise as an ongoing at-sea training opportunity. More formally, this may serve as a replacement for volunteers, which would be beneficial because seasickness is the main challenge to recruiting volunteers for cruises. In this way, a pre-cruise sea day (e.g., on the Sproul) could serve as a test run prior to the scheduled CalCOFI cruise. CalCOFI would also like to continue to support institutions in integrating CalCOFI data into course content (e.g., across the UC system). Fundamental to all of these efforts is diverse engagement, especially of early career ocean professionals. CalCOFI will continue to work toward ways to recruit and integrate early career ocean professionals into the CalCOFI program and have a clear path to retain their connection (e.g., REUS to grads to postdocs to early career research and policy positions in CalCOFI). In addition, CalCOFI would like to have a way to track career trajectories of early career professionals that have been involved in and trained within CalCOFI. CalCOFI will also continue to expand the research and data science opportunities such as through individual projects and hackathons.

K-12 and community engagement. CalCOFI will continue to explore partnerships with outreach organizations to effectively engage in outreach and education with California's public schools, especially those in underserved communities, to bring CalCOFI's data and history into school classrooms. For example, CalCOFI could consider an oceanography summer camp for underrepresented minorities in partnership with an organization like SCOPE. CalCOFI would also like to increase efforts to conduct outreach to inland communities in California.

Communications. CalCOFI will continue to expand its communications capacities in partnership with California Sea Grant and partnering organizations communications teams. CalCOFI could develop a communications team that consists of the CalCOFI technicians that are skilled in communications as well as members from partnering communications teams. In addition, CalCOFI is interdisciplinary in nature and will continue to work toward exploring novel ways to communicate about the CalCOFI program. For example, CalCOFI could develop an artist-in-residence program that works closely with CalCOFI ship operations, researchers, and practitioners to communicate about the CalCOFI program.

ACKNOWLEDGMENTS & REPORT PREPARATION

This report was prepared by the CalCOFI Committee (Drs. Brice Semmens, Noelle Bowlin, Julia Coates, Ralf Goericke, Rasmus Swalethorp, Andrew Thompson, and Briana Brady) and the CalCOFI Coordinator (Dr. Erin Satterthwaite) with input from the CalCOFI core program personnel (Angela Klemmedson) and utilizing information compiled from CalCOFI Committee meetings, past CalCOFI strategic documents (e.g., previous reports and reviews), stakeholder input from the 2019 Stakeholder Workshop presented in the CalCOFI Stakeholder report (Engeman et al. 2020), survey responses from over 500+ participants from the 2020 CalCOFI Conference, past CalCOFI white papers (e.g., Stocks & Baker 2005), and a literature and web search review.

The photos and images in this report are courtesy of Angela Klemmedson, Rasmus Swalethorp, Laura Lilly, Jim Wilkinson, Emily Gardner, Natalya Gallo, Michael Ready, Chase Martin, and Erin Satterthwaite.

Recommended citation: Satterthwaite, E.V., Semmens, B., Bowlin, N., Coates, J., Goericke, R., Swalethorp, R., Thompson, A. Brady, B. & CalCOFI personnel. 2021. Long-term marine ecosystem observations to support sustainability & resilience in the California Current System: California Cooperative Oceanic Fisheries Investigations (CalCOFI) 2017 - 2021.

SUPPORTING DOCUMENTS & APPENDICES

Appendix 1: CalCOFI Data Inventory 2021

Appendix 2: Species sampled by CalCOFI

Appendix 3: CalCOFI management relevant species

Appendix 4: CalCOFI Publications 2017-2021

Appendix 5: CalCOFI Events 2017-2021

Appendix 6: CalCOFI Presentations 2017 - 2021

Appendix 7: Institutions affiliated with CalCOFI

Appendix 8: Early Career mentees

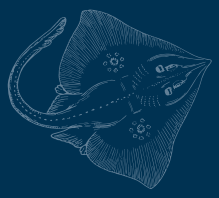
Appendix 9: CalCOFI Volunteers

Appendix 10: CalCOFI website metrics

Appendix 11: CalCOFI in the media

Appendix 12: CalCOFI Personnel

Appendix 13: CalCOFI Funding 2017-2021



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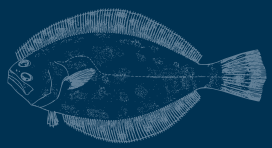

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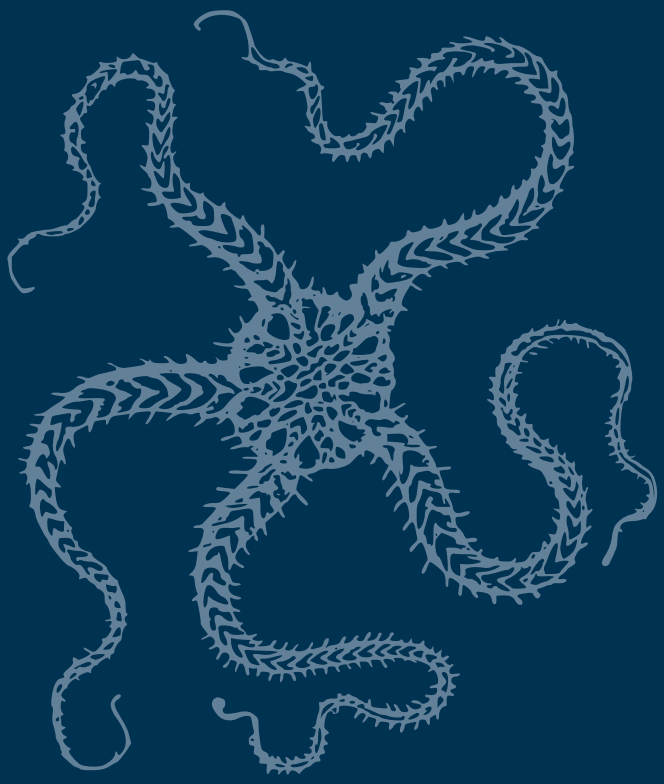

"Nothing has such power to broaden the mind as the ability to investigate systematically and truly all that comes under thy observation"

~Marcus Aurelius