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TITLE OF PROPOSED PROJECT **Ecological Transitions in the California Current Ecosystem: CCE-LTER Phase II**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 5,640,000	72 months	08/01/10	

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Ecological Transitions in the California Current Ecosystem: CCE-LTER Phase II

Project Summary

The California Current Ecosystem (CCE) LTER site is a productive coastal upwelling biome structured by remote and local physical forcing, as well as biotic interactions in the ocean water column. The CCE site, building upon 60 years of extensive time-series measurements by CalCOFI, seeks to understand the mechanisms underlying transitions between different states of this ecosystem, as well as their corollary: ecosystem resilience. In the first phase of CCE funding we uncovered a new climate mode for the North Pacific (NPGO); found marked differences in food web structure between the offshore wind stress curl and the classical coastal boundary upwelling domains; detected long-term changes in gelatinous grazers (pelagic tunicates), optical properties, nitracline depths, prevalence of hypoxia, stratification, and other ecosystem characteristics; revealed zones of iron and iron-light co-limitation of primary production; developed a ROMS model and used it in hindcast mode to diagnose causality of ecosystem transitions and forecast mode to guide Lagrangian process cruises; developed an allometric approach to food web modeling; discovered differences between physical and biotic time series in degree of nonlinearities; demonstrated the destabilizing effects of fishing; initiated new data practices; and more. Our first phase results point to the importance of spatial structuring of the CCE, especially on the mesoscale. In this renewal we target mesoscale fronts and eddies, which constitute an important part of the CCE ecological disturbance regime. We have found that such features vary on interannual and decadal scales in the CCE region and we hypothesize that their variability over time may contribute to ecosystem transitions.

Our overarching questions are: **What are the mechanisms leading to different states in a coastal pelagic ecosystem? What is the interplay between changing ocean climate, community structure and ecosystem dynamics?** To address these questions, we are evaluating 4 mechanisms that could contribute to ecosystem transitions: *anomalous alongshore advection; in situ food web changes in response to stratification and nutrient supply; changes in cross-shore transport;* and *altered predation pressure.* We will also test 3 hypotheses related to the role of mesoscale processes, specifically concerning their role in altering nutrient fluxes and predator-prey interactions, the integrated biogeochemical effects of mesoscale fronts and eddies over the CCE region, and the relationship of such features to larger scale climate variability. A combination of Lagrangian process cruises, experimental work, time series measurements, modeling, data synthesis, and a coupled human-natural system study will be used to address these questions. We will also continue to measure the 5 LTER core variables.

Broader Impacts: Notable among the ecosystem services furnished by the coastal ocean off southern California is the region's importance for spawning and/or harvesting of many commercially important fishes and marine invertebrates. Our research will provide a key scientific foundation for understanding time and space variability of properties relevant to ecosystem-based fisheries management. This information is essential as managers begin to address the consequences of changing ocean acidity, stratification, and hypoxia for resource populations and communities. Our ISSE (Integrated Science for Society and the Environment) study will partner an economist, graduate student, and scientists in the development of a bioeconomic model to examine the interplay between ecosystem variability and fishers' decision-making and resource allocation. In addition, we will further develop and enhance DataZoo, the information system central to our Information Management and data sharing environment. We will implement new web-accessible tools to facilitate data visualization and communication of CCE results to students, teachers across all levels, scientists, managers, policy-makers, and the broader public. Our Education, Outreach, and Capacity Building (EOCB) program will include a vigorous program of involvement of tens of graduate students in site science and communication. A graduate student will serve as a research liason with the EOCB coordinator, to help translate CCE science into K-12 lesson plans. We will work with local teachers in a diverse urban school district to bring CCE science into the classroom, and will continue our outreach and coastal ocean time series with the nonprofit Ocean Institute. We will expand our highly successful RET and Teacher-at-Sea programs, to enable teachers to communicate the process of science inquiry directly to students. We will continue our REU program, targeting under-represented undergraduates in order to expand the pipeline into the ocean sciences.

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For font size and page formatting specifications, see GPG section II.B.2.

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Section 1. ***Results from Prior LTER Support***

LTER: Nonlinear transitions in the California Current Pelagic Ecosystem OCE-0417616, $4,920,000 + supplements, Sept. 2004 - Aug. 2010

The California Current Ecosystem (CCE) Long-Term Ecological Research site was initiated in August 2004 with the goal of understanding the mechanisms underlying ecosystem state changes in a coastal upwelling ecosystem. Our over-arching questions are: ***What are the mechanisms leading to different ecosystem states in a coastal pelagic ecosystem? What is the interplay between changing ocean climate, community structure and ecosystem dynamics?*** Thanks to our interaction with CalCOFI (the *California Cooperative Oceanic Fisheries Investigations*), an important space-resolving time series program (Fig. 1-1), we had a 55-year head start that provided important evidence for changes in ecosystem properties on multiple time scales. We have now successfully launched the CCE-LTER site. Here we report on selected results from the first funding cycle. We also mention some important progress that has been enabled by Supplemental Funding. We then mention briefly Cross-site Interactions, the CCE Information Management program, and our Education, Outreach and Capacity Building program. In its first 5½ years, CCE has produced > 140 publications (108 journal articles, 5 book chapters, 1 children's book, 12 conference proceedings and reports, and 12 PhD and 2 masters theses; Appendix 1 and http://cce.lternet.edu/publications/).

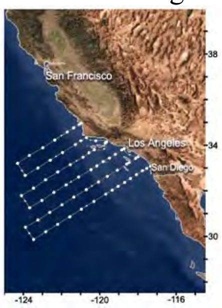

Fig. 1-1. CalCOFI sampling stations; used for collaborative CCE quarterly cruises.

A. Long-term changes in the California Current Pelagic Ecosystem

NPGO – a new climate mode. When we initiated this LTER site, the primary mode of climate and ecosystem variability in the NE Pacific was thought to be the Pacific Decadal Oscillation (PDO). Recently CCE scientists led by Emanuele Di Lorenzo defined a new climate mode called the North Pacific Gyre Oscillation (NPGO), which is related to the "Victoria mode" of sea surface temperature (Bond et al. 2003) and the "breathing mode" of sea level height (Cummins and Freeland 2007). It represents the oceanic response to the North Pacific Oscillation of atmospheric sea level pressure and links physical ocean changes with diverse biological variables in the eastern North Pacific (cf. Fig. 1-2, Di Lorenzo et al. 2008, *GRL*). Many previous results on decadal variability were thereby placed into the context of this new understanding of the physics, a result which has attracted considerable interest in the community. The NPGO may eventually be used for diagnostics of climate regimes and possibly even forecasting of biotic responses.

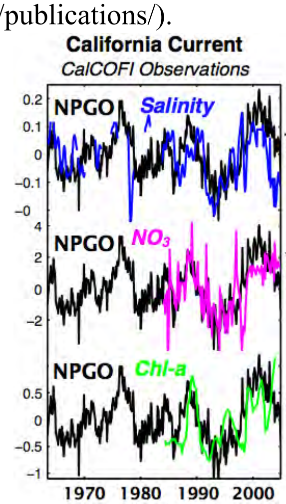

Fig. 1-2. NPGO and 3 co-variates, from the CalCOFI region.

Wind stress curl-driven upwelling and its effects on the pelagic food web. A study led by CCE graduate student Ryan Rykaczewski revealed a key ecological distinction between the effects of wind stress curl-driven upwelling in the California Current System and the conventionally studied coastal boundary upwelling (Rykaczewski and Checkley 2008, *PNAS*). The curl-driven upwelling zone is located much farther offshore and is characterized by slower vertical upwelling velocities than upwelling at the coastal boundary. However, because curl-driven upwelling affects a much larger ocean area, it represents a larger flux of nutrients into surface waters. Working on CCE process cruises, Rykaczewski and Checkley (2008) found that the zooplankton size spectrum is strongly related to upwelling velocities and that spatial differences in zooplankton body size are closely associated with differences in prey preferences of two planktivorous fishes, the Pacific sardine (ingests smaller prey) and northern anchovy (larger prey). The long-term increase in curl-driven upwelling documented by these authors explains the preferential growth of sardines. This work extends mechanistically from 'physics to fish' and partially explains a long-standing enigma about how sardines and anchovy could fluctuate out of phase in the same ocean region.

Destabilizing effects of fishing pressure. Another CCE graduate student-led study analyzed over 50 years of CalCOFI ichthyoplankton data and compared the variability of fish species that are subject to harvesting with a 'control' group of species that co-occurs in the same ocean habitats but is not harvested (Hsieh et al. 2006, *Nature*). The harvested species consistently showed greater variability through time, even after controlling for differences in life history traits and phylogenetic history. This and subsequent results (Anderson et al. 2008) suggest that fishing pressure destabilizes populations by truncating age class structure, a result with both theoretical and important management implications.

Nonlinear biological responses to linear physical forcing. Some of the same authors analyzed a group of time series from the North Pacific and uncovered a major dichotomy between the dynamics of physical and biological variables (Hsieh et al. 2005, *Nature*). They observed that all of the physical time series were explained best as stochastic linear processes. In contrast, all of the biological time series (Scripps pier diatoms, CalCOFI copepods and fish larvae, catch of 5 species of salmon) showed nonlinear dynamics. The implications of this study are significant: nonlinear biological responses (including regime shifts) often occur, even if the underlying physical environment is changing linearly. This implies that programs such as OOI and NEON must not rely on physical proxy variables to interpret the dynamics of biotic populations. Hsieh and Ohman (2006, *Ecology*) later proposed the Linear Tracking Window hypothesis to explain when populations can act as linear amplifiers of physical variability.

Other climate-scale changes detected in the CCE region

CCE research has uncovered several other climate-scale influences that markedly affect ecosystem processes and ecosystem services.

- Long-term decline in pelagic tunicates (mainly salps) in the CCE region (Lavaniegos and Ohman 2007). Salps play a disproportionate role in the vertical flux of organic carbon and could be a contributor to the long-term variations in benthic communities that CCE scientist Ken Smith and his group have measured on the deep-sea floor (cf. K. Smith et al. 2008; 2009).
- Increased density stratification in the water column of the CCE region (Kim and Miller 2007).
- Decline in dissolved oxygen from 1984-2006, resulting in the shoaling of the hypoxic boundary and a decrease in the oxygenated, habitable portion of the water column (Bograd et al. 2008).
- Increasing concentrations of NO_3 and PO_4, in parallel with declines in dissolved oxygen, but with altered N:P ratios in California Undercurrent waters. These changes affect nutrient availability in source waters that are upwelled in the CCE region (Bograd in prep.; Chhak and DiLorenzo 2007).
- Increasing phytoplankton concentrations and inferred primary production in the California Current and other eastern boundary currents, from a 12-year record of satellite imagery (Kahru and Mitchell 2008; Kahru et al. 2009).
- Declines in Secchi disk depth (a measure of optical transparency) since 1949 and shoaling of the nitracline since 1984 (Aksnes and Ohman 2009), paralleled by higher phytoplankton concentrations. These results counter conventional expectations associated with stronger vertical density stratification.
- Gradual increase in Chl *a*, and earlier shift in timing of the spring bloom, from the Scripps pier time series over 18 years (Kim et al. 2009).
- Variability in the amplitude and phasing of coastal upwelling in the CCS, which may lead to phenological changes for diverse organisms (Bograd et al. 2009).

B. The space-for-time exchange: developing the mechanistic basis for ecosystem forecasting

CCE experimental Process cruises are based on a "space-for-time exchange," i.e., the hypothesis that spatial variability observed in the system can be used as an analog for how a given region may change over time. This conceptual picture ties our shipboard experimental work to the time scale of climate change and to mechanistic understanding of ecological transitions. Three highly successful CCE Process cruises were completed with NSF support (spring 2005 and 2006, fall 2008) and a graduate student-led cruise supported by UC Ship Funds was completed in April 2009, modeled after CCE cruises. All used a Lagrangian approach (water-parcel following), exploiting the range of physical-chemical environmental variability to determine the extent to which **stratification and nutrient supply** drive predictable and quantifiable changes in primary production and phytoplankton composition, and propagate to higher trophic levels.

In addition to our scientific results, these Lagrangian studies are noteworthy because of the new tools that permit us to locate and track discrete water parcels in a dynamic upwelling environment, which has always been challenging. Using satellite-tracked drifters, *Spray* gliders, Moving Vessel Profiler surveys, Advanced Laser Fluorescence results (Chekalyuk and Hafez 2008), satellite imagery, and, for one cruise, a ROMs forecast model, we were usually able to identify and track such water parcels successfully.

Phytoplankton growth and grazing dynamics in an upwelling environment. We conducted experiments to test the hypothesis that local dynamics of phytoplankton are determined, to first order, by the difference between phytoplankton growth rates and grazing losses. Following satellite-tracked drifters for periods of 3-5 days, independent measurements of growth and grazing rates (by micro- and mesozooplankton) explained 91% of the variability observed in net growth rates of the ambient phytoplankton (Landry et al. 2009), providing strong support for the growth-grazing hypothesis. Mean growth rates of phytoplankton were highest 50-100 km offshore in the upwelling flow off Point Conception. Differences mainly in mesozooplankton grazing led to a positive-to-negative shift in phytoplankton net rates of change between two spring cruises under comparable growth conditions, suggesting strong top-down control potential.

Fe limitation and Fe-light co-limitation of phytoplankton. Then graduate student Andrew King documented the potential for episodic iron limitation of phytoplankton in this system, with associated effects on macronutrient utilization, community species composition, and phytoplankton spatial and temporal distribution (King and Barbeau 2007). Novel findings from CCE-LTER also extend to the deep chlorophyll maximum layer. Former graduate student Brian Hopkinson obtained some of the first field evidence for iron-light co-limitation of subsurface phytoplankton communities underlying macronutrient-limited surface waters from studies conducted in affiliation with CCE-LTER (Hopkinson and Barbeau 2008). Iron availability may therefore have the greatest potential to affect subsurface phytoplankton communities when light levels increase rapidly, such as during isopycnal shoaling associated with mesoscale eddies. The influence of iron on phytoplankton community structure at subsurface chlorophyll maxima has consequences for nutrient cycling and carbon export within the lower euphotic zone.

Numerous other results from the experimental Process cruises are in preparation, including assessment of bacterial growth rates and ectoenzyme activity in relation to a new class of transparent particles (FFP or Filter Fluorescing Particles) discovered by graduate student Ty Samo; particle fluxes measured by the thorium disequilibrium method and by sediment traps (M. Stukel); particle characteristics from autonomous floats (D. Checkley); analysis of particle size spectra (D. Taniguchi); spatial differences in phytoplankton pigment groups measured by Advanced Laser Fluoresence (Chekalyuk and Hafez 2008) and by HPLC (R. Goericke); other bio-optical characterizations (G. Mitchell and H. Wang) and remote sensing validation measurements (M. Kahru); shifts in microplankton community composition (M. Landry and A. Taylor); DOC and DON characterization (L. Aluwihare lab); omnivory by dominant species of copepods and euphausiids (M. Décima); changes in mesozooplankton vertical habitats in relation to water column optical characteristics (M. Ohman); multi-frequency bioacoustic assessment of small pelagic fishes and micronekton (T. Koslow and A. Lara); glider-based acoustic estimates of mesozooplankton (J. Powell); carbon export flux due to migratory mesopelagic fishes (P. Davison).

C. Modeling and other synthetic activities

We have developed an advanced physical circulation modeling environment for our site, to explore the relationship between the dynamics of ocean circulation and ecological processes in the ocean water column. The Di Lorenzo and Miller labs have developed an ocean modeling framework, using eddy-resolving Regional Ocean Modeling System (ROMS) in a nested configuration over the northeast Pacific. A sub-model includes nutrient-phytoplankton-zooplankton-detritus (NPZD) and an iron limitation component developed in collaboration with UC Santa Cruz (Fiechter et al. 2009). This model framework has been essential to recognition of the NPGO (Di Lorenzo et al. 2008), passive tracer experiments analyzing the sources of upwelled waters in different phases of the PDO (Chhak and Di Lorenzo 2007), budgets of the upper ocean and their relationship to decadal dynamics of the PDO and NPGO (Chhak et al. 2009), development of a forecast for Process cruise site selection, and other CCE advances.

Data from the CCE Process cruises have been used to parameterize and validate models that reproduce/predict the variations in C:Chl ratios and growth rates of phytoplankton throughout the region (Li et al. submitted), and to model food web flows through size-structured consumers in relation to measured estimates of export flux from the euphotic zone (Stukel et al. in prep.). The size-resolved, spatially-resolved set of ecosystem rates from the Process cruises will also be used for testing the allometric model developed by Fuchs and Franks (in prep.), which predicts connectance and planktonic size spectra based on the prey size preferences of the predators (i.e., specialist vs. generalist zooplankton).

Qian Li, another postdoc, has configured the NEMURO size-structured model using CCE size-resolved growth and grazing data. Comparison of modeled vs. measured growth rates shows that the model accurately predicts both the vertical and cross-shore variability in phytoplankton growth rate (Li et al. submitted). This model can now be used to explore the ramifications of changed physical and chemical environments on the planktonic ecosystem.

D. Cross-site interactions

Although a new arrival, CCE has worked to participate fully in LTER network activities. CCE presented at the LTER mini-symposium at NSF in Feb. 2005. In fall 2005, CCE helped organize a session for the *U.S.-Japan Workshop on Global Change Research* in Yokohama coordinated by John Magnuson. CCE has been well represented at 2 ASM meetings (2006, 2009). At the most recent, M. Ohman co-led a workshop on ocean acidification. CCE co-authored an article (Ohman and Hobbie 2008) on *Aquatic Research in the U.S. LTER Network*, and contributed a passage to the article (Porter et al. 2009) on advanced sensors for ecology. CCE has been actively involved in the EcoTrends project, including on the Editorial Board of EcoTrends from the beginning, and Ohman and Kratz (2010) co-authored a chapter on climate effects. Ohman led an EcoTrends discovery workshop at the Science Council meeting in Portland (2007), and others from CCE participated in the Ecosystem Services workshop for the same meeting.

Several CCE people participated in the planning grant activities that led to ISSE (the Meeting of 100, climate change and other working groups), a subsequent workshop on Social Ecological Systems in Puerto Rico, and participated in subsequent planning for a Coastal Zone Climate Change plan at the spring 2009 Science Council meeting and the 2009 ASM.

CCE collaborated with PAL scientists to produce the *Sea Secrets* children's book, has recently discussed parallels with PAL in the EcoTrends State Changes working group, and foresees other interactions with PAL. Representatives from the 3 LTER sites based in California (CCE, SBC, and MCR) have prepared joint proposals to the University of California Office of the President and to a UC-National laboratories cooperative program, and we anticipate other collaborative work in the future. Information managers from all 3 sites have met with one another, and several seminar speakers have presented at the other LTER sites. In May 2008 a consortium of graduate students and postdocs from SBC, MCR, and CCE met in La Jolla; a 2nd meeting occurred at the ASM in Estes Park in 2009, and a 3rd is planned for 2010.

In network governance, M. Ohman has served on the Executive Board and CCE members currently serve on the Climate Committee, NISAC, as editor of LTER Databits, Schoolyard Executive Committee, the Children's Book Committee, and the EcoTrends Editorial Committee. CCE hosted the 2009 Science Council meeting (La Jolla, May 2009).

E. Results from Supplemental NSF Support

- Schoolyard supplements have led to the development of a vigorous Education and Outreach program by our coordinator Beth Simmons (see below and in section 5). Supplement awards have also enabled:
- Information Management – Creation of a data dictionary, integration of visualization/plotting software for DataZoo, and a planned U.S.-Finnish effort on global IM infrastructure development.
- U.S.-Japan international collaborations – A joint *International Workshop on Collaborative Studies for Ecosystem Variation and Climate Change in the North Pacific* in Yokohama in Oct. 2006 was co-organized by CCE, and attended by 4 CCE researchers and 2 CCE graduate students. The discussions led to a research collaboration between D. Checkley and Yoshioki Oozeki of the National Research Institute of Fisheries Science, Yokohama in July 2009. A manuscript is in preparation based on that collaboration.
- Seabird observers – These funds supported the seabird observer program on an augmented CalCOFI cruise in 2008, and all data have been QC'd and entered into CCE's DataZoo.
- Equipment purchases. **ISUS nitrate sensor** – This has been an important tool for resolving nitracline variations in the CCE site, and has also been used by CCE graduate students for special projects. **Mooring sensors** – The purchase of key sensors made it possible to deploy a first deep water biogeochemical mooring (CCE-1) in the low salinity core of the California Current (http://mooring.ucsd.edu/index.html?/projects/cce/cce_data.html). **Laser Optical Plankton Counter (LOPC)** – The replacement LOPC has been received and will be deployed on the next CCE-augmented CalCOFI cruise. **Trace Metal clean rosette** – A trace metal grade rosette plus Go-Flo bottles have been ordered and will soon be available in support of CCE site science. ***Spray* ocean glider** – This will add an ISUS-equipped glider to our glider program, which has operated in the CCE site since Oct. 2005.

F. Information Management

The CCE Ocean Informatics Group, led by Karen Baker, has constructed a comprehensive CCE website http://ccelter.sio.ucsd.edu/. They have developed an innovative data serving environment called DataZoo (http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/datasets), with an architecture staged to meet growing needs for data presentation, documentation, integration, analysis and exchange. CCE has fully adopted and implemented EML. A digital event logger, networked between shipboard laboratories and the ship's bridge, has been developed and is used regularly at sea. A 6-module zooplankton website: the *Cooperative Zooplankton Dataspace* (http://oceaninformatics.ucsd.edu/zooplankton/) has been created to serve as a portal to mesozooplankton data. The Ocean Informatics group has also mentored several students, providing them experience with interdisciplinary collaborative science. A more complete account of the IM program may be found below in section 4.

G. Education, Outreach, and Capacity Building (*http://cce.lternet.edu/outreach)*

Under Beth Simmons' leadership our Education, Outreach and Capacity Building program has developed actively. Simmons co-wrote the children's book *Sea Secrets: Tiny Clues to a Big Mystery*, which was hatched at the CCE site and developed as a collaboration between CCE and PAL. It has been very well received, including at a 'family day' book signing at the Birch Aquarium at Scripps, and is part of the UNEP International Polar Year Project (http://www.unep.org/Publications/polarbooks/books/1015.aspx). We have also involved over 1200 schoolchildren in at-sea data collection through our chlorophyll-temperature time series project at the nonprofit Ocean Institute at Dana Point, CA, and developed diverse instructional materials. We have involved 4 certified teachers in RET experiences (2 taken to sea, who wrote highly popular "Teacher at Sea" blogs), and we have supported summer research projects for 13 REU students (http://cce.lternet.edu/outreach/). Different educator groups have visited our site, from middle and high schools. Our ecosystem approach has been featured in SIO *Explorations* magazine and elsewhere. Numerous presentations have been made to teachers, school groups, Open Houses at SIO and UCSD, invited testimony given before the U.S. House Subcommittee on Fisheries and Oceans, the CA Council on Science and Technology, and other public venues. Forty-four graduate students, 13 postdocs, and 21 technical staff have participated in CCE research cruises, experiments, and modeling. Five graduate courses and 3 undergraduate courses have incorporated results from CCE science. The EOCB program is more fully explained below in section 5.

Section 2. ***Conceptual Framework***

Preamble: Response to mid-term site review

The report of the mid-term panel that reviewed the CCE site in Sept. 2007 began: "*The panel's overall assessment of this program was* ***strongly positive***." [emphasis in the original]. Here we respond briefly to the highly constructive suggestions from that panel.

I. Site-level Research

1. *Create conceptual diagrams representing both the overall program goals and circulation features of the study area.* – We have created both diagrams (see Figs. 2-2 and 2-7) and already find them very useful.

2. *Entrain additional physical oceanographic expertise.* – We have added three new physical oceanographers (Jennifer MacKinnon, Rob Pinkel, and Chris Edwards) as Associates and more fully engaged others already in the CCE site, including in planning for the cruises focusing on mesoscale processes.

3. *Instrument/platform maintenance/replacement plan* – We are expanding the funding base for our glider and mooring programs to include SCCOOS and NOAA support.

4. *Focus some of the next 6-year phase on process studies associated with disturbance* – Disturbance regimes – especially as represented by mesoscale fronts and eddies – have become the major new focus of the present proposal.

5. *Expand the scope of the modeling effort to include top predators* – Since the time of the review, a graduate student developed a new paradigm for the role of pelagic fishes in our region (Rykaczewski and Checkley 2008). In addition to new work on such fishes in the renewal, we have expanded our seabird/marine mammal observer program. These observational data are essential for model validation. We also have a new postdoc (Diego Macias) whose modeling studies will include examining top-down effects of fish in the CCE region.

II. Cross-site, network, and international research

1. *Increase dialog with freshwater ecologists within the LTER Network* – Collaborations with freshwater ecologists are growing. A collaborative chapter (Ohman and Kratz 2010) has been written for EcoTrends, and an invited overview of aquatic research in the US LTER Network published in the ASLO Bulletin (Ohman and Hobbie 2008). We made contributions to a cross-biomes sensors article (Porter et al. 2009). Productive interactions are developing with NTL (and others) in the State Changes working group. We look forward to even more interactions with freshwater ecologists in the future.

2. *Increase efforts at collaboration with the Santa Barbara Channel LTER site* –CCE has now met with SBC on several occasions, including the preparation of two joint proposals outside the LTER network. We have held an SBC-CCE site exchange in La Jolla and at least 3 CCE PI's have given seminars at UCSB. We also hosted a CCE-SBC-MCR graduate student/postdoc symposium, and another such meeting occurred at the Sept. 2009 All-Scientists Meeting, with a third exchange planned for Sept. 2010. We have numerous common interests with SBC, especially with scientists focusing on the water column, and are continuing to expand those interactions.

III. Outreach and Education

1. *"The panel recommends staying with the present course for this element of the program."* – We believe we have sustained (and even expanded) the vitality of our E&O program. In addition, our REU program is now beginning to enhance diversity, and we are active in the LTER children's book program.

IV. Information Management and Information Technology

1. *Continue to improve "Datazoo" to enhance usability by researchers* – The dataserving/datasharing elements of DataZoo have been extremely positively received. Ease of use for novices has now been improved by providing direct links to pre-made plots for signature datasets and core variables.

2. *Develop a more comprehensive policy on data and data sharing* – We now have a comprehensive data policy covering data submission, acknowledgement, and use components. We have an open data sharing model for all participants at the site, and data are posted to be in compliance with the NSF 2-year rule.

3. *Pursue reciprocal web links between CCE LTER and affiliated programs* –Reciprocal web links from CalCOFI and other related programs have now been implemented.

4. *Continue to make data available online and increase participation in the LTER Network Data Catalog* – We have now significantly expanded our postings of data on the LTER Network Data Catalog. At the time of the site review, we were 2½ years into a new program and in the midst of designing and implementing a comprehensive site metadata model. We have a more direct and timely data delivery process and are updating our metadata description procedures.

V. Site/project Management

1. *Develop an annual Graduate Student Symposium* – CCE graduate students and postdocs now hold a nearly annual symposium. This has been held either for CCE participants alone or in collaboration with SBC and MCR students and postdocs.

2. *Add an External Advisory Committee* – After discussion, the CCE EXCO decided to create a rotating external participant or two, rather than a standing committee with permanent membership. One or more outside participants will now attend our annual meetings. The expertise we seek will depend on the primary issues/results we are considering. In addition, as we have a relatively large group of PI's and Associates (N=28), we have decided to draw on more of the diversity of perspectives within our site by adding an additional member to our EXCO.

Conceptual Framework: Brief overview of planned research

The California Current Ecosystem (CCE) LTER site is a coastal upwelling biome forced by physical processes on a variety of time and space scales. The southern sector of this region has been an ideal location for an LTER site for many reasons: it is the site of the 60-year CalCOFI ocean time series; it encompasses a biogeographic boundary region and is an early sentinel of climate change; it is representative of productive pelagic coastal upwelling biomes; it is the preferred spawning site for ~ 90% of epipelagic fish biomass in the southern sector of the California Current System, as well as for many nearshore fishes and benthic invertebrates; low frequency changes in this region are correlated with changes in much of the NE Pacific; and there is a large gradient of ocean conditions from oligotrophic to highly productive, over a small geographic distance, encompassing much of the range of productivity in the world ocean.

The CCE-LTER site will continue to focus on the **mechanisms underlying ecosystem transitions,** or ecological state changes, in our coastal pelagic upwelling ecosystem. We will test 4 mechanisms leading to such transitions and assess the effects of forcing that operate on different time scales, including: progressive long-term changes (e.g., ocean warming, changes in stratification, ocean acidification), decadal-scale variations of a quasi-periodic nature (e.g., NPGO and PDO), and interannual perturbations (e.g., ENSO). In addition, we will exploit the natural spatial heterogeneity within our LTER site in a space-for-time exchange: i.e., the hypothesis that spatial variations in food web structure and rate processes in the pelagic community can be used as an analog of how a region may be expected to change over time. A major new element of our proposed research is an enhanced focus on mesoscale processes as a modulator of long-term ecosystem variation in the CCE region. We will characterize the mesoscale disturbance regime using a variety of measurement methods (robotic ocean gliders, satellite remote sensing, shipboard measurements, and moored observations). During Process Cruises, we will test the hypothesized effects of mesoscale eddies and associated fronts on nutrient fluxes, growth and grazing rates, and prey-predator interactions. Modeling studies will bridge the temporal and spatial scales of long-term observations and process experiments in assessing the effects of variations in meso- and larger scale dynamics on the pelagic food web. A new CCE program element at the interface of human and natural systems will address the interaction of fishers' decision-making with ecosystem variability. We will continue to measure the core variables of importance to all LTER sites: disturbance regimes, inorganic nutrients, organic matter, population studies, and primary production.

Our LTER site is structured around 6 program elements: Experimental Process Cruises, Time-series Observations, Modeling, Information Management, Education, Outreach, and Capacity Building (EOCB), and a new ISSE (Integrated Science for Society and the Environment Initiative) program.

Unifying Theme and Approach

The CCE-LTER site encompasses a dynamic coastal upwelling ecosystem, which exhibits variability on many time and space scales. The principal focus of the CCE site has been on lower-frequency temporal variations of the ecosystem, including those that operate on interannual, decadal, and multi-decadal time scales (see Results from Prior LTER Support). Sometimes such variations are accompanied by relatively abrupt transitions between ecosystem states (e.g., Fig. 2-1). The causal mechanisms leading to such **ecosystem transitions** remain our primary interest. While research in the CCE-LTER site and elsewhere has demonstrated the influence of physical drivers on marine ecosystems, both theoretical and a variety of empirical studies in this region have now revealed nonlinear responses of pelagic populations that cannot be accounted for by the physical environment alone (e.g., Hsieh et al. 2005; Hsieh and Ohman 2006). Small, progressive changes in the physical environment can lead to abrupt transitions in ecosystem state (e.g., de Young et al. 2008, Scheffer et al. 2009). Thus, we are interested in the interactions of both biotic and abiotic processes that contribute to a propensity for rapid change in ecosystem state and in its corollary: resilience to ecosystem perturbations. In order to progress to a quantitative understanding of such ecosystem transitions that can eventually be used to forecast their ecological effects, we are building from our excellent observational records toward an understanding of the mechanistic basis underlying both ecological changes and persistence.

In our previous funding cycle we focused primarily on changes in the mean conditions across the CCE study site. During the course of the first funding phase of the CCE program, we have developed an increased appreciation for the importance of spatial structuring of the site, in addition to the spatially averaged mean conditions. Results from our first funding cycle identified the different food webs in the offshore wind stress curl upwelling zone of slow upwelling (Rykaczewski and Checkley 2008) in contrast to the nearshore coastal boundary upwelling zone of high upwelling velocities (Fig. 2-2). We have identified a broad range of different nitracline depths (i.e., depth where the dissolved nitrate concentration first exceeds 1µM, Fig. 2-4) across our study site, which is related to spatial differences in optical properties (Asknes et al. 2007; Aksnes and Ohman 2009) and phytoplankton community structure (Collier and Palenik 2003; Goericke in prep.). We now recognize zones of iron-limited growth of phytoplankton (King and Barbeau 2007) and iron-light co-limitation (Hopkinson and Barbeau 2008, Fig. 2-3) and are beginning to understand the consequences of spatial variations in nutrient supply for growth and grazing processes (e.g., Landry et al. 2009) and pelagic community structure. In the process, we have developed an interest in the importance of spatial discontinuities associated with mesoscale fronts and eddies (Figs. 2-5, 2-6, 2-7), whose changes over time may play a large role in the flux of nutrients and the outcome of predator-prey interactions. Hence, this renewal proposal retains a focus on ecosystem transitions, but newly addresses the ecological disturbance regimes associated with mesoscale fronts and eddies as a key component of the longer-term changes in the system.

The central questions we will address in the CCE-LTER site remain:

What are the mechanisms leading to different ecosystem states in a coastal pelagic ecosystem?

What is the interplay between changing ocean climate, community structure and ecosystem dynamics?

We have identified four principal mechanisms that could lead to the observed ecosystem shifts in the California Current pelagic ecosystem (such as those depicted in Fig. 2-1):

- **Sustained, anomalous alongshore advection of different assemblages --** Temporal variations in north-south transport introduce organisms of different geographic origins into the southern sector of the California Current Ecosystem
- **In situ food web changes in response to altered stratification and nutrient supply -** Changes in the species structure, trophic connections, and pathways of energy flow occur in response to changes in water-column vertical stratification and incidence of mesoscale fronts and eddies. Stratification modifies the rate of supply of limiting nutrients (whether macronutrients or trace metals) for phytoplankton production. Altered nutrient supply leads to altered rates of primary production and/or compositional changes in the phytoplankton assemblage, which propagate through the food web.
- **Changes in cross-shore transport and loss/retention of organisms** -- Temporal changes in the rates of cross-shore transport, via either mean flow or propagation of mesoscale eddies, modify the probability of retention of nutrients and organisms in the nearshore coastal zone.
- **Altered predation pressure** -- Altered abundances (or dietary shifts) of planktivores lead to selective mortality and altered abundances and composition of the planktonic food web.

We will continue to evaluate each of these mechanisms in the next six years of our LTER site, although the approaches taken will differ among the mechanisms considered. Our experimental focus will be on ***in situ*** **food web changes**, with particular attention to the role of mesoscale features. The remaining mechanisms (changes in **alongshore advection, cross-shore transport/retention** of organisms, or **predation pressure**) will be evaluated through time-series measurements and modeling studies, as described below. We recognize that these mechanisms are not mutually exclusive and that each of these hypothesized mechanisms may be involved to different degrees.

In light of our enhanced interest in the mesoscale disturbance regime, in addition to lower frequency perturbations, we intend to address the role of mesoscale features in the balance of CCE production, biomass accumulation, nutrient and trophic fluxes, and predator-prey interactions. This issue is particularly relevant to our LTER site because of the preliminary evidence (below) that these mesoscale features show long-term variations on a climate scale. We intend to test the following specific hypotheses in connection with the mechanisms above.

H_1: Perturbations associated with mesoscale fronts and eddies include altered nutrient transport to the euphotic zone, modified primary production, shifts in plankton community structure, altered predator-prey interactions, and altered vertical export of organic matter.

H_2: Processes associated with mesoscale physical features dominate biogeochemical fluxes, when integrated over the CCE region.

H_3: Variability in the frequency and intensity of mesoscale features, and their associated impacts on biogeochemical cycling and ecosystem dynamics, can be explicitly linked to larger scale climate variability (e.g., NPGO, PDO, and ENSO).

We now describe the ongoing CCE-LTER program, followed by a description of the proposed enhancements: the effects of mesoscale dynamics on the CCE and the consequences of environmental uncertainty for fishers' harvesting decisions.

The California Current System (CCS) and Ecosystem (CCE)

The California Current is the eastern limb of the large, clockwise circulation of the subtropical gyre of North Pacific Ocean (Fig. 2-7A). As part of the water from the westwind drift turns southward and becomes the California Current, it carries cool, fresh water from the subarctic. The California Current *System* off central and southern California consists of the broad, eddy-rich southward flowing California Current (CC), a persistent but variable subsurface California Undercurrent (CUC) centered on the continental slope that carries water of tropical origin poleward, and a circulation over and near the continental shelf that is energetic and highly seasonal, shifting from a wind-driven equatorward flow and coastal upwelling in spring-summer to poleward flow in fall-winter (Hickey 1998).

Along much of the U.S. west coast, especially during the spring and summer, the North Pacific High pressure system yields winds from the north that drive near-surface waters offshore by Ekman transport, and cool nutrient-rich water from below is advected toward the surface in the near-shore zone. This wind-driven coastal upwelling is a characteristic feature of eastern boundary currents (Hill et al. 1998). Upwelling also occurs offshore of the coastal margin, associated with curl of the wind stress (i.e., upwelling induced by an onshore-to-offshore gradient in the intensity of alongshore winds; see Fig. 2-2).

The mean circulation of the CC includes several large-scale permanent meanders linked to coastal promontories (Centurioni et al. 2008). Closer to the shoreline, coastal upwelling jets occur during upwelling events in spring and summer months (Barth et al. 2000). The CC and the upwelling jets are unstable and produce vigorous mesoscale variability (Marchesiello et al. 2003), with jets that carry upwelled water hundreds of kilometers offshore, sharp fronts and well-defined eddies, particularly during the upwelling season and near coastal promontories. Eddy energy varies with the seasons, typically peaking in summer, and eddies propagate energy westward away from their generation regions in the CCS (Kelly et al. 1998; Strub and James 2000; Di Lorenzo 2003). Mesoscale eddies have typical velocities of 30 cm/s, as large as the CC core, with peaks of 80 cm/s (Chereskin et al. 2000; Davis et al. 2008). Eddy amplitudes (dynamic height anomaly of 0.15 dyn m) can be as large as the total steric height increase across the CC; hence, the mean southward flow of the CC is often disrupted by strong mesoscale features (Figs. 2-7B,C).

Point Conception, near the northern boundary of our study region, is a coastal promontory associated with strong upwelling and mesoscale variability. The sharply angled coastline has a marked effect on coastal winds (Winant and Dorman 1997), but the CC continues southward, while a series of submarine banks and ridges extend the continental barrier on the inshore side of the current. Inshore, the southward moving mix of subarctic and upwelled waters interacts with warm-water intrusions from offshore and the south; together these form a counterclockwise circulation pattern, the Southern California Eddy, which dominates the Southern California Bight (Dong et al. 2009).

The strength and location of the CC and of the inshore circulation vary seasonally, interannually and interdecadally in response to large-scale changes in ocean/climate patterns. The northern part of the CC is mainly driven by changes in the Aleutian Low and is associated with the Pacifical Decadal Oscillation (PDO) pattern of SST (Chhak et al.; 2009). The southern part of the CC is mainly driven by the changes in the North Pacific Oscillation (NPO) and is associated with the North Pacific Gyre Oscillation (NPGO) pattern of SST. Remote forcing from the tropics, associated with El Niño and La Niña events, also drives CC variations through coastally trapped poleward propagating oceanic waves and related atmospheric teleconnections.

These dominant climate forcing patterns control the mean circulation and strength of eddy energy to a large degree in the CCS, resulting in a mixture of source waters that varies concordantly. The physical and chemical heterogeneity of the CCS south of Pt. Conception makes the region well suited for studying the dynamic responses of pelagic ecosystems to mesoscale and larger scale climate forcing.

The CCS has pronounced onshore-offshore differences in nutrient delivery mechanisms and food-web structure along the California coastline (shown schematically in Fig. 2-2) which have been used to distinguish the habitat domains of the dominant small pelagic fishes, anchovy and sardine (Rykaczewski and Checkley 2008). The main physical driver is the gradient in surface wind stress, which peaks offshore, a phenomenon accentuated in our region by the sharp southeastward break in the orientation of the California coastline south of Point Conception. Close to the coastal boundary, offshore Ekman transport of surface waters under upwelling favorable (equatorward) winds draws cold, nutrient-rich water (including iron infusions from the sediments) into the euphotic zone, resulting in strong blooms of larger phytoplankton taxa (diatoms and dinoflagellates), which in turn support elevated concentrations of large consumers, notably large calanoid copepods and euphausiids. This classic coastal upwelling domain (anchovy habitat) is characterized by a high-biomass, relatively shallow euphotic zone and unbalanced food web processes, in which growth rate excesses over consumption losses (Landry et al. 2009) promote rapid biomass accumulation and ultimately large export. Farther offshore (sardine habitat), the horizontal shear in wind stress (the wind stress curl) drives a more subtle Ekman divergence of surface transport that drives a vertical input of water from the deeper nutricline into the base of the euphotic zone. The nutrient flux associated with curl-driven upwelling is small per unit area compared to that from coastal boundary upwelling, but substantial in the aggregate because it occurs over a much more extensive area. As presented schematically in Fig. 2-2, the lower rate of nutrient delivery selects for smaller primary producers (flagellates and photosynthetic bacteria) that compete most effectively for nutrients at low concentration. These are regulated effectively by small protistan consumers, resulting in a tight coupling of growth, grazing and nutrient recycling processes. The offshore region is also typically characterized by strong density stratification and a deep maximum in chlorophyll *a* (and microbial biomass) at the base of the euphotic zone, where diminishing light meets the top of the nutricline. We hypothesize that the contrasts in food web structure shown in Fig. 2-2 also occur on much smaller scales, including across some types of mesoscale features.

The CCE region is a major center of spawning of epipelagic fishes (including Pacific sardine, northern anchovy, Pacific hake, jack mackerel), many of which migrate extensive distances to spawn in this region in preference to upwelling centers elsewhere in the California Current System (Saunders and McFarlane 1997; Smith and Moser 2003). The preference for this habitat has been hypothesized to relate to the more retentive ocean circulation in the region (e.g., Parrish et al. 1981; Bailey 1981) and, in the case of sardines, to the prey size spectrum favored in the curl-driven upwelling region (Rykaczewski and Checkley 2008). The very large historical variations in landings of these fishes have been attributed to the interaction of natural ecosystem variations (cf. Fig. 2-1) and human fishing decisions (Jacobson et al. 2001; Hsieh et al. 2005), both of which will be addressed in the CCE site (see ISSE section below).

Mesoscale Physical and Biological Dynamics in the CCS

Our field and modeling work has increasingly revealed the importance of the physical and biological dynamics associated with mesoscale fronts, meanders and eddies (Figs. 2-7, 2-8). As we detail below, the intensity and frequency of mesoscale features change over time, and these changes may play a large role in the flux of nutrients and the outcome of predator-prey interactions. While this renewal proposal retains a focus on ecosystem transitions, we propose an enhanced focus on the ecological disturbance regimes associated with mesoscale fronts and eddies as a key component of the longer-term changes in the system. Here we introduce the dynamics of fronts, meanders and eddies, demonstrate that these features have significant interannual variability in the CCS, and show that they can have pronounced chemical and biological consequences in our region.

Physical circulations of mesoscale features: fronts, meanders and eddies

As in the atmosphere, oceanic fronts are formed by strong horizontal density gradients. Less dense (warm/fresh) water on one side of the front abuts more dense (cold/salty) water on the other side. This creates a pressure gradient that would tend to drive the light water over the heavy water. However, this tendency for water to flow in the direction of the horizontal pressure gradient is countered by the Coriolis force, which turns currents to their right in the northern hemisphere. Over time scales >1 day and length scales greater than ~10 km, the horizontal pressure gradient and the Coriolis forces can balance, leading to a stable front. This leads to an along-front jet, usually strongest on the light side of the front. The balance of the pressure gradient and Coriolis forces is known as the "geostrophic" balance or "geostrophy;" the balance of these two forces allows stable horizontal density gradients to exist.

Fronts are not always long, straight features in the ocean, but often show bends or meanders. Frontal bends create secondary patterns of vertical circulation along the isopycnal surfaces forming the front. If we look down the front in the direction of the jet in the northern hemisphere a front bending to the right (anticyclonic) tends to drive an upwelling of water along isopycnals, due to the conservation of potential vorticity (Fig. 2-8; Cushman-Roisin 1994). A front bending to the left (cyclonic) drives downwelling. Since a perfect geostrophic balance does not allow vertical motions of the water, these secondary quasi-geostrophic or ageostrophic motions are fundamentally important to biological processes. However, they are only apparent when we look at the full 3D dynamics of the front.

Frontal meanders can grow in size through a process called "baroclinic instability:" a small meander can grow to the point that it pinches off to form an eddy. An eddy is therefore basically a front that has closed in on itself. The water inside the eddy can either be more dense (cold core) or less dense (warm core) than the surrounding waters. Isopycnals of a warm-core eddy form a bowl shape, trapping nutrient-poor waters in the eddy center. Isopycnals of a cold-core eddy form a shape like the bell of a downward-pointing trumpet, with cold, nutrient-rich waters at its core. The nonlinear dynamics within the eddies and interactions among eddies can drive significant vertical velocities both at the eddy centers and edges. These vertical velocities involve dynamics in addition to the geostrophic terms, and often occur on shorter time and smaller spatial scales.

Fronts, meanders and eddies form at time and space scales known as the "mesoscale." Mesoscale physical dynamics are ubiquitous, and are an important source of biological disturbance in the ocean.

Long-term variations in mesoscale activity in the CCS

Observational as well as modeling studies conducted by the CCE group suggest that there is significant long-term variability in mesoscale frequency and intensity in the CCS. This variability in mesoscale activity could contribute to the observed transitions between ecosystem states in the CCE. In one study, the frequency of fronts detectable in satellite-derived sea-surface temperature images revealed strong interannual variability in the CCE region (Fig. 2-9, Kahru and Manzano in prep.). Peaks in front frequency are correlated with the Northern Oscillation Index (Schwing et al. 2002), an index of climate variability based on the difference in sea level pressure anomalies between the North Pacific high pressure zone and Darwin, Australia. The NOI includes ENSO variations in the North Pacific, suggesting that some of the interannual mesoscale variability our region is associated with ENSO's.

Eddy-resolving modeling studies (Di Lorenzo et al. in prep.) have revealed a relation of wind stress variability to mesoscale activity in the CCS and eastern Pacific (Fig. 2-10). A stronger gradient of the wind stress curl leads to a stronger California Current, and in turn, stronger instabilities of the flow: mesoscale eddies. The observed long-term variations in the wind stress curl gradient thus lead to significant interannual and decadal fluctuations in the intensity of mesoscale features in the CCE region. Model tracer experiments show that mesoscale eddies move westward from the California coast, transporting material offshore (Fig. 2-11, Combes et al. in prep). By tracking individual eddies over time, we have found a marked decrease in Chl *a* concentrations over time as the eddies age (Fig. 2-12), indicating that predictable biotic changes occur within these mesoscale features (Kahru unpubl.).

Our modeling framework thus gives us the capability to retrospectively analyze interannual variability in cross-shore and vertical fluxes associated with mesoscale eddy dynamics.

Mesoscale features as Disturbance Regimes

There is strong evidence that there is interannual and decadal variability in the frequency and intensity of mesoscale features in the CCE region (Figs. 2-9 and 2-10). Here we show that these fronts and eddies have a significant local and regional biological impact.

A wealth of studies have explored the physics, chemistry and biology of fronts and eddies (Belkin et al. 2009). Some particularly notable studies of oceanic fronts and eddies include the EDDIES and E-Flux programs (e.g., Deep-Sea Research II Vol. 55(10-13), 2008), the CTZ experiment (e.g., Journal of Geophysical Research Vol. 96(C8) 1991), the Warm-Core Rings program (e.g., Deep-Sea Research A 33(11-12), 1986), and the CCS eddy study (Progress in Oceanography Vol. 13(1) 1984). In general, these studies revealed strong horizontal gradients of physical, chemical and biological properties across the fronts and eddy boundaries. The isopycnal slopes and circulation patterns associated with eddies influence the efficacy of surface wind stresses in driving vertical mixing (e.g., McGillicuddy et al. 2007). In cyclonic eddies, the upward tilting of the isopycnals enhances nutrient flux at the eddy center which often fuels the growth of larger phytoplankton, particularly diatoms (e.g., Brown et al. 2008; Landry et al. 2008a). The degree of enhancement of biomass can be related to the age of the eddy, with older eddies showing less pronounced increases in growth rates, grazing rates and biomasses than younger eddies (but see Rii et al. 2008).

Biological selection and community responses that lead to the broader CCE spatial domain differences depicted in Fig. 2-2 also operate at the smaller scales of fronts, through the regulation of nutrient fluxes. Nitrate, iron, silicic acid and phosphorous can limit phytoplankton growth, depending on the oceanic region and phytoplankton group considered (Moore et al. 2002; 2004). Physical dynamics that force limiting nutrients such as nitrate from the deep pool in the aphotic zone into the euphotic zone (e.g., McGillicuddy et al. 2007; Ledwell et al. 2008) lead to increased phytoplankton growth rates and biomass (Haury et al. 1993; Landry et al. 2008a), and altered plankton size structure (Eisner and Cowles 2005; Landry et al. 2008a). These upward nutrient fluxes effectively change the planktonic ecosystem from an oligotrophic-type community dominated by small plankton to a more eutrophic community with an increased fraction of large organisms. Patches of enhanced phytoplankton at fronts (e.g., Franks 1992) can also be sites of enhanced bacterial production (Ewart et al. 2008), zooplankton biomass and grazing (Haury 1984; Eden et al. 2008; Landry et al. 2008b), larval fish (Moser and Smith 1993), and a mechanism of organic matter export out of the euphotic zone as particles or DOC (Barth et al. 2002).

In previous eddy studies in the CCE region, zooplankton communities showed sharp discontinuities at the fronts (Haury et al. 1986). Copepod egg production has been shown to respond to fronts associated with coastal jets (Smith and Lane 1991) and copepod naupliar abundance can be altered at upwelling or downwelling fronts (Smith et al. 1986). Fronts are also important feeding or spawning grounds for marine top predators, and thus the targets of fisheries (Polovina et al. 2001). In the southern California Current ecosystem, seabirds as well as other top predators such as tuna have been associated with fronts (Fiedler and Bernard 1987; Yen et al. 2006). It has also been suggested that offshore eddies provide habitat that favor survivorship of larval sardines (Logerwell and Smith 2001; Logerwell et al. 2001). Numerous studies have related marine birds to fronts and eddies in coastal and open ocean habitats (e.g., Kinder et al. 1983; Hunt et al. 1996; 1998; reviewed by Hunt 1997). In shelf waters, seabirds respond to fronts produced by the interaction of local circulation with bathymetric discontinuities such as seamounts or other shallow topography (Yen et al. 2004). The distribution of seabirds has also been related to frontal structures in the open ocean (O'Hara et al. 2006). In all cases it is thought that seabirds concentrate at fronts due to increased prey availability, though rarely has this been demonstrated empirically (but see Hunt et al. 1996; 1998).

The same physical dynamics that drive upward nutrient fluxes at fronts can also drive downward fluxes of organic carbon. As described for a cyclonic frontal meander of the CCS off northern California (Shearman et al. 1999; Barth et al. 2002), downwelling along isopycnals caused by conservation of potential vorticity in the meander led to the subduction of a patch of chlorophyll to >200 m depth over a period of ~25 days. The eventual sinking of ~5 such patches to the benthos was estimated to have the potential to satisfy the organic carbon requirements of the benthic community within 300 km of the coast for a year. Subduction of similar patches at fronts has also been observed in the CTZ region of northern California (Washburn et al. 1991; Hood et al. 1991).

The physical mechanisms described above lead to pronounced *local* biological responses. Mesoscale physical dynamics can also create patchiness and disturbance through stirring of existing hydrographic, chemical and biological gradients (e.g., Davis et al. 2008). This can be clearly seen in satellite remote sensing: the stirring of warm and cold waters is usually matched by similar patterns in phytoplankton pigments. Cold temperatures usually represent nutrient-rich waters with high chlorophyll concentrations, while warm temperatures indicate more oligotrophic regions. This stirring of existing gradients is usually superimposed on the local biological responses, which can enhance or dissipate the patchiness. Furthermore, the local biological responses are often most pronounced below the surface, where they are invisible to remote sensing.

Mesoscale features – fronts, meanders and eddies – may thus influence the CCE region via altered nutrient supply, export fluxes, lateral transports, and aggregation of a variety of mobile predators. The enhancement of these dynamics at mesoscale features may cause them to be disproportionately important to the spatially integrated fluxes. Long-term variations in the frequency and intensity of mesoscale features may thus be a mechanism driving long-term fluctuations in ecosystem properties in the CCE.

CCE-LTER *A-front* study

To explore the ecosystem consequences of mesoscale features in the CCE region, we allocated one day to a brief pilot study on the CCE-LTER Process Cruise in October 2008. Designated the A-front study, it was carried out ~230 km from the coast in ~3700 m of water. The front was identified by satellite imagery (Fig. 2-5A), by repeated crossings with a Moving Vessel Profiler that sampled to 200 m depth while the ship was underway (Fig. 2-5D), and by continuous near-surface flow-through measurements with an Advanced Laser Fluorescence (ALF, Chekalyuk and Hafez 2008) system. Two of several characteristics measured by ALF include phycoerythrin fluorescence at 565 nm (Fig. 2-5B) and phytoplankton variable fluorescence (Fv/Fm, Fig. 2-5C). All variables revealed sharp lateral gradients.

Following this initial survey we carried out a south-to-north series of measurements at stations intended to sample the frontal gradient region and the assemblages on both sides of the front. The results revealed a number of features, including elevated photosynthetic quantum yield, highly elevated bacterial growth rates, enhanced diatom biomass, elevated abundance of both calanoid copepods and copepod nauplii, and elevated fish biomass (determined acoustically) at or near the peak frontal gradient region (Fig. 2-6). In contrast, some taxa showed disjunct distributions at the front, with *Prochloroccus* spp. biomass elevated south of the front and *Synechococcus* biomass elevated to the north (Fig. 2-6).

We now intend to extend these preliminary results, to understand the processes that generate enhanced nutrient fluxes and primary and secondary production in such frontal regions, and the exploitation of such mesoscale features by higher trophic levels, including fishes and seabirds. Our research will be guided by the specific hypotheses delineated above.

Approaches to address mechanisms of nonlinear ecosystem transitions

Anomalous alongshore advection: The importance of sustained, anomalous alongshore advection as a mechanism leading to changes in assemblages and maintenance of altered assemblages will be addressed by calculating the north-south volume transports through the cross-shore trending lines in the LTER sampling domain. Vertically integrated transports will be computed from the dynamic topography obtained on quarterly time series cruises and more frequent *Spray* glider missions, to assess whether alterations in the biota are coincident with altered transports. Higher frequency sampling at the CCE-1 offshore mooring (equipped with an ADCP), as well as the CORC (Consortium for the Ocean's Role in Climate) moorings along CalCOFI line 90 (http://mooring.ucsd.edu/index.html?/projects/cce/cce_data.html) will permit finer temporal resolution of variations in transport.

In situ food web changes: Given the present unpredictable nature of ecosystem changes, we cannot be assured of capturing an appropriate temporal transition within a funding cycle. In order to address the hypothesis of **in situ food web changes** in the face of this temporal uncertainty, we will exploit the spatial variability in the southern sector of the CCS and the wide dynamic range of ocean conditions that exist at any given time within our study domain. These conditions range from the productive nearshore coastal upwelling region off Pt. Conception, to the offshore region of wind stress curl upwelling, to the highly oligotrophic, stably stratified region on the edge of the central North Pacific Gyre. We will utilize a **space-for-time exchange**, i.e., we will exploit this natural spatial variability as an analog for how food web structures and rate processes might be expected to respond to temporal changes in environmental forcing. For our experimental process studies we will focus on different characteristic spatial regions defined by phytoplankton floristic analyses and water column characteristics, representing the end-member states of pelagic ecosystem structure (strong upwelling, to curl upwelling, to stably stratified) and a continuum of conditions in between. We will simultaneously carry out time-series measurements that will enable us to test the assumption that variations in space are appropriate analogs for variations over time. We very successfully used this space-for-time exchange approach in our first funding cycle.

***Anomalous cross-shore transport and loss/retention of organisms*:** Altered cross-shore transports as a mechanism leading to altered rates of retention of organisms in the near-shore zone will be addressed by inferring the rates of Ekman transport from the near-surface wind field measured on CalCOFI cruises and by hindcast runs of the ROMS model that allow computation of lateral and vertical fluxes due to mesoscale eddies (E. Di Lorenzo and A. Miller). Calculations of property fluxes using the Control Volume approach (see Fig. 2-13) will provide a constraint on the accuracy of the mean volume transport calculations. Observed eddy-related cross-shore fluxes can be assessed by computing temporal changes in front frequency and eddy occurrence from AVISO satellite altimetry data. These estimates will be supplemented by studying the ROMS model runs, which allow a complete diagnostic breakdown of the fluxes due to mesoscale eddies that cannot be adequately resolved by observations.

Altered predation pressure: The predators of primary interest are the zooplanktivorous fishes and carnivorous zooplankton. Variations in zooplanktivorous fish stocks (sardines, anchovies, jack mackerel) will be determined by colleagues at the Southwest Fisheries Science Center/NMFS. Bioenergetic models will be used to estimate consumption by fish schools under high and low prey availability that may result from changes in stratification (e.g., Nonacs et al. 1998). Variations in abundance of carnivorous zooplankton (esp. jellyfish, siphonophores, chaetognaths) will be assessed from the CalCOFI zooplankton samples. Attention will be paid to temporal changes in the occurrence of the mesoscale eddies and front frequency, and their associations with abundance of the predators.

Core LTER Research Areas

In the course of our hypothesis-oriented research in the CCE LTER site, we will continue to address core measurements held in common among all LTER sites. We look forward to developing more comparative studies across sites, such as those stimulated by the EcoTrends project.

Pattern and control of primary production: Rates and patterns of primary production will be measured by ^{14}C uptake incubations on four cruises per year in our LTER site. Such measurements have been made since 1984 in the CalCOFI region, although for the LTER program we measure the rate of production of *dissolved* as well as *particulate* organic carbon. In addition to *in situ* measurements, we have parameterized algorithms to estimate primary productivity (Kahru et al. 2009) from satellite remote sensing. Our investigations of controls of primary production include the effects of macronutrient limitation, iron limitation, and irradiance on phytoplankton specific growth rates for several algal subgroups. The role of grazing pressure by nano-, micro-, and meso-zooplankton will be addressed on experimental Process cruises.

Spatial and temporal distribution of populations selected to represent trophic structures: We will focus on representative organisms representing different trophic levels as well as "sentinel species," many of which are already known to provide excellent indications of responses to ecosystem changes in the CCS. These organisms will be sampled or sighted (seabirds) four times per year on the CalCOFI sampling grid, characterizing spatial as well as temporal variability. They are: **Bacteria** - heterotrophic prokaryotes; **Phytoplankton** – *Procholorococcus*, *Synechococcus*, selected diatom and dinoflagellate species; **Particle-feeding zooplankton** - selected species of copepods, salps and doliolids; **Omnivorous zooplankton** - selected euphausiid species; **Carnivorous zooplankton -** selected hydromedusae and siphonophores**; Zooplanktivorous fish** - Pacific sardine, northern anchovy and jack mackerel; **Seabirds** - Sooty Shearwater, Cassin's Auklet, Rhinoceros Auklet, Cook's Petrel and Black-vented Shearwater.

Aggregated measures of total biomass of phytoplankton (as Chl *a* and HPLC chemo-taxonomically defined categories), nano- and micro-zooplankton (from image-analysis based microscopy), and mesozooplankton (from size-based reconstruction using ZooScan, as well as displacement volume) will also be assessed. Changes in mesozooplankton vertical distributions will be determined by Laser Optical Particle Counter four times per year.

Pattern and control of organic matter accumulation and decomposition in surface layers and sediments**:** As part of our integrated studies of upper water column production controls on Process cruises, we measure the rate of organic matter export from the euphotic zone using the thorium disequilibrium method and sediment traps. Sedimentary accumulation and utilization of organic matter is addressed by CCE Associate Ken Smith at his long-term deep sea time series station at Sta. M (Fig. 2-15, below). Smith and co-workers characterize the time-varying flux of particulate organic carbon to sediments in the deep sea, its oxidation, and consequences for benthic macrofauna communities. We also intend to further analyze the relationship between the epipelagic zooplankton community and fluxes of organic matter reaching the sea floor.

Patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters**:** Fluxes of nutrients are a central issue in this site and will be addressed in our time series studies, experimental studies, and modeling efforts. Time series observations, again on the quarterly augmented CalCOFI cruises, will assess spatial patterns of nutrient concentrations and nutricline depths as well as nutrient input into the euphotic zone via upwelling and horizontal transport. Experimental studies will evaluate sensitivity of different parts of the phytoplankton assemblage to co-limitation by macronutrients, iron, and light. Control Volume calculations (Fig. 2-13) will evaluate the dynamic balance between geostrophic convergence into our study site and Ekman divergence out of our study site, permitting us to constrain the major sources and sinks of nutrients in this system (e.g. Roemmich 1989; Bograd et al. 2001).

Patterns and frequency of disturbances**:** Disturbance influences are fundamental to this LTER site. We will characterize disturbances on many scales, using (1) continuous measurements from the Scripps pier, *Spray* ocean gliders, and the CCE moorings in the Southern California region (Fig. 2-15), (2) high frequency temperature and phytoplankton pigment profiles from our Education and Outreach associate, the Ocean Institute, located in Dana Point, CA, (3) satellite remote sensing measurements, including MODIS-Aqua and MERIS ocean color and sea surface temperatures, (4) quarterly shipboard measurements of hydrographic, meteorological, plankton, and ichthyoplankton characteristics, and (5) communication with colleagues who use paleoceanographic proxies to characterize longer term variability from the varved sediment record of the Santa Barbara Basin.

Components of the CCE- LTER program

Overview

The CCE-LTER program is now comprised of 6 inter-related components. These include our Experimental Process studies, Time-Series studies, Modeling program, ISSE (Integrated Science for Society and the Environment Initiative) program, Information Management group, and Education, Outreach, and Capacity Building (EOCB) programs. Each of these program elements interdigitates with the others. All program elements are represented on the CCE Executive Committee. We will introduce the first four listed program elements here, while Information Management and EOCB are described below in separate sections of the proposal.

Experimental Process Studies

Three CCE Process cruises are planned for the proposed funding period, each of 30 days duration during the spring-summer period of greatest mesoscale variability (see glider-derived structure function in Fig. 2-16). The proposed timing of the cruises in 2011, 2012 and 2014 (ends of years 1, 2 and 4) will concentrate the field experiments toward the beginning of the funding period and allow sufficient time for full sample and data analysis, assimilation into models, and publication of results before the next phase of CCE research. While specific features and phenomena cannot be predicted precisely in advance, previous cruises have shown strong frontal and eddy structures from which to choose. The experiences on these cruises have also sharpened our ability to utilize real-time satellite imagery, glider sections, and data-assimilating physical models initialized with hydrographic data from preceding CalCOFI cruises to identify and respond to the research opportunities as they appear in the study region. We therefore envision an operational strategy that is flexible and adaptable to contemporaneous conditions, but built upon structural elements and experimental approaches that we have applied successfully in our recent processes studies.

We envision process cruises with three major components – 1) survey mapping of the mesoscale feature of interest, 2) detailed sampling and experimental studies in the region of influence of the front, and 3) comparative sampling and experiments conducted in adjacent waters outside of the feature (see Fig. 2-17). Survey mapping will be conducted before and after experimental studies to resolve the 3-D structure of the feature, its areal footprint relative to what can be resolved in surface satellite imagery, and its change with time. Survey data will be used in 4DVAR data assimilation studies (described below) to diagnose vertical velocities, estimate diffusivities, and calculate fluxes. Detailed measurements in the feature, as well as on repeated transect sampling across the front (e.g. Fig. 2-17), will document its effects on biogeochemical and ecological stocks and rates. Comparative studies of adjacent waters will allow us to evaluate whether stocks and rates are enhanced in the feature and to sustain continuity of datasets begun during the first phase of CCE.

Survey Mapping**:** Once a feature of interest has been identified in satellite imagery and confirmed with preliminary sections with our Moving Vessel Profiling (MVP) system, we will use the SIO SeaSoar system for more detailed mapping. Compared to the MVP, this system is relatively cumbersome to launch and recover, but it carries a much larger payload of instruments (CTD, oxygen, PAR, ISUS nitrate, fluorometer, transmissometer, Laser OPC, and echosounder) for characterizing the physics, chemistry and biology of the water column, and is therefore a more efficient platform for continuous sampling operations that are expected to last for 3-4 days (Fig. 2-17).

SeaSoar survey mapping from the surface to approximately 300 m will be complemented by continuous surface sampling by the ship's MET system (including surface T, S and ADCP current profiles) and by a flow-through Advanced Laser Fluorometer (ALF), which provides pigment-based spectral deconvolution of major phytoplankton groups and F_v/F_m assessment of phytoplankton photo-physiological state (Chekalyuk and Hafez 2008). Higher level animals that likely associate with subsurface structures in the water column will be surveyed with a multi-frequency acoustical sampling (Simrad EK-60 with 38, 70, 120, and 200 kHz), which distinguishes krill, small schooling pelagic fish and their larger predators using dB-differencing techniques based on the different frequencies of reflectance as a function of organism size and presence/absence of swim bladders (Korneliussen and Ona 2003). During daylight hours, seabirds will also be censused along the survey track using standard underway observer techniques (Tasker et al. 1984) to document concentrations and species associations in the vicinity of frontal features.

Detailed Sampling and Process Measurements**:** Satellite-tracked drifters with mixed-layer drogues (15 m) and attached thermistor chains will be deployed from the research vessel in the frontal features studied and in adjacent experimental water parcels as points of reference for repeated sampling. The drifters will also help interpretations of horizontal and vertical water movements during the semi-synoptic SeaSoar surveys. We will use experimental drifters as we have in the past for Lagrangian-based sampling and daily experimental studies in which we can compare the net rates of change of populations observed during daily sampling to the net rates predicted by the sum of measured process rates (e.g., Landry et al. 2009). These will be shorter (1-2 day) experiments, compared to 4-5 day experiments previously run, to allow for repeated comparison experiments in and out of the feature closely spaced in time, as opposed to distinctly separate blocks of experiments at the different sites over potentially changing physical conditions. At fronts, drifter incubation experiments will be augmented by sampling along lines orthogonal to the axis of the feature (Fig. 2-17) to characterize the spatial extent of the frontal region and assess the down-stream fates of biota or biomass that are advected away from the frontal system. Frontal subduction zones are likely to show strong signatures of enhanced Chl, absorbance (beam c) and particles (LOPC) along deepening isopycnal surfaces. Such depth strata can be identified in short daily sampling with the MVP, and explored in detail with discrete sampling with the CTD rosette and net collections.

Experimental operations on CCE Process cruises typically occur as cycles of interrelated stock and rate measurements, beginning with predawn CTD hydrocasts to sample the system at 8 light depths spanning the euphotic zone. Measured variables include: standard CTD (T, S, density, PAR, O_2), nutrients (dissolved inorganic N, P, Si), total organic carbon and nitrogen (TOC, TN), particulate carbon and nitrogen (POC, PON), fluorometric Chl *a* and HPLC accessory pigments, and microscopical and flow cytometric assessments of microplankton community composition, all of which are analyzed by the same methods used for the augmented CalCOFI time series (Fig. 2-20). Additionally, routine samples are taken for particulate biogenic silica (BSi; Brzezinski and Nelson 1995), stable isotopes of C and N (Owens and Rees 1989; Fry et al. 1992), and assessment of export flux by the thorium-uranium disequilibrium method (Pike et al. 2005). The same CTD water collections are also used to determine taxon-specific rates of phytoplankton growth, ^{14}C-primary production and microzooplankton grazing impact by a combination of dilution and pigment labeling approaches (Goericke and Welschmeyer 1993; Landry et al. 2009), which are conducted as 24-h incubations in net bags attached on a line below the drift array. Separate morning sampling with GO FLO bottles is done to measure the concentration and depth distribution of iron (Fe) and to assay for Fe-limation using shipboard-incubated grow-out experiments (e.g. King and Barbeau 2007; Hopkinson and Barbeau 2008). Occasionally samples are taken to examine temporal-spatial changes in microbial genetic diversity (Huse et al. 2008).

Following the moving reference of the drifters, additional sampling is conducted at mid-day for bio-optical profiles (spectral backscattering, absorption, attenuation, profiling reflectance radiometry, fast repetition rate fluorometry; Loisel et al. 2000; Stramska et al. 2000), for pigments and POC/PON, and for shipboard assessments of primary production (Mague et al. 1980), PvsE relationships (Sosik 1996), bacterial production (^3H-leucine; Simon and Azam 1989; Smith and Azam 1992), bacteria-particle interactions and enzyme activities (Martinez et al. 1996). MOCNESS net tows are taken at mid-day and mid-night to determine the depth structure and day-night variability of the mesozooplankton community. Sampling of mesopelagic fishes and invertebrates is conducted with a large (5 m^2) mid-water trawl net (Oozeki et al. 2004) to assess the contribution of actively migrating mid-water animals to organic export from the euphotic zone and to ground-truth stock inferences from multi-frequency acoustics. Bongo net tows are also taken around mid-day and mid-night for depth-integrated assessments of zooplankton biomass structure and gut fluorescence in the euphotic zone (Landry et al. 2009). One side of the paired nets from these collections is preserved for species identification. The other is size-fractioned on shipboard for biomass (dry weight, C, N) and gut pigment analyses. On several occasions during a cruise, bongo net collections are taken at 3-4 h intervals over 24-h to better resolve the diel periodicity in feeding (gut fluorescence) and migration into the euphotic zone. Additionally, various experimental studies are conducted throughout the cruise to assess the grazing rates, selective behaviors and reproductive outputs of individual dominant mesozooplankton species feeding on the naturally occurring spectrum of available prey. At least twice during each cycle, McLane pumps are used to collect large volume samples from below the euphotic zone for C:Th ratios and the estimation of carbon export by the thorium disequilibrium method (Buesseler 1998).

Nutrient fluxes will be estimated using independent techniques. Vertical diffusivities will be estimated from CTD and thermistor data using Thorpe scale analysis (Thorpe 1977) and measurements of the vertical strain of the internal wave field (Thompson et al. 2007). These vertically resolved diffusivities will be combined with vertical profiles of nitrate concentration to obtain a vertical flux. Diapycnal and isopycnal fluxes of nutrients in the study region will also be estimated through assimilation of hydrographic and physical data from the surveys into models (see below).

The sampling strategy defined above is designed to compare the states of the system inside and outside of mesoscale features in terms of the concentrations and distributions of biogeochemical variables, the biomass and/or abundances of major components of the biota from microbes to fish and seabirds, and the processes of primary production, taxon-specific phytoplankton growth, micro- and mesozooplankton grazing, bacterial growth and production and export fluxes due to particles and active migrants.

Time-Series Observations

CCE-LTER will be using diverse approaches to observe the state of the ecosystem and its changes over time and space. The core LTER measurements will be carried out in conjunction with the CalCOFI program using ships as sampling platforms. Other platforms, such as satellites, *Spray* ocean gliders, instrumented moorings, a deep-sea benthic observatory, and shore/coastal stations, are acquiring data at higher temporal and spatial frequencies to complement the shipboard sampling (see Fig. 2-15). Our approach leverages existing assets and programs, e.g. the CalCOFI program, satellites, NOAA-funded moorings, and draws strength from the existing long-term time series of many core variables dating as far back as 1916, or in the case of the CalCOFI data set, to 1949.

The measurements that are made can be characterized as (1) discrete in time (quarterly CalCOFI augmented sampling) or semi-continuous (nearshore observations ranging from ~biweekly in the case of the Ocean Institute Chl *a* time series, to minutes in the case of the automated instruments deployed on moorings and piers) and as (2) offshore (CalCOFI, gliders, moorings, satellites) or nearshore (OI and SIO Pier). This approach allows us to observe at least some system variables at virtually all relevant temporal and spatial scales.

Semi-Continuous Measurements

Scripps Pier: Temperature has been measured at the SIO pier since 1916, and other properties for varying lengths of time. While measurements were first made on discrete water samples, today conductivity, sea surface temperature, pressure, and Chl *a* fluorescence measurements are semi-continuous. SIO Pier temperature is used as an environmental index for the management of the Pacific sardine (Hill et al. 2008).

Ocean Institute (OI): Our Education and Outreach associate in Dana Point (www.ocean-institute.org), makes ~150 student cruises per year on a 70-ft vessel to an oceanographic station in close proximity to CalCOFI station 90.28. Since 2005 OI has conducted CTD casts and analyzed samples for total phytoplankton biomass and the picoplankton component (both as Chl *a*) to help us assess the propagation of Kelvin waves (e.g., during the onset of El Niño) and to engage students directly in this research project.

"Spray" *Ocean gliders* (spray.ucsd.edu): The *Spray* glider program was initiated in the CCE site in Oct. 2005 by M. Ohman and R. Davis. We use robotic ocean gliders invented and built by the Davis lab at SIO to measure temperature, salinity, density, phytoplankton Chl *a*, zooplankton acoustic backscatter, and Doppler shear from the sea surface to 500 m along two sampling lines that run orthogonal to the main axis of flow of the California Current (Fig. 2-15). We will soon add nitrate measurements to the gliders.

CCE Biogeochemical moorings (mooring.ucsd.edu/index.html?/projects/cce/cce_intro.html): We have deployed telemetering moorings in the offshore low salinity core of the California Current (CCE-1) and the coastal boundary upwelling zone (CCE-2), to understand interrelationships between pCO_2, O_2, pH, NO_3, phytoplankton, zooplankton/fish acoustic backscatter, and acoustically recorded marine mammals.

Southern California Coastal Ocean Observing System (www.sccoos.org): SCCOOS maintains CODAR sites (for radar-detected surface currents) in the Southern California Bight (SCB), provides funds for measurements such as the Scripps Pier and CalCOFI nearshore stations, and acts as a clearinghouse for data collected in the SCB or derived from models of the regions.

Satellite Remote Sensing (spg.ucsd.edu/Satellite_Projects): Satellite sensors will be used to estimate sea surface topography, winds, temperature, and concentrations of Chl *a*, dissolved colored organic matter, suspended sediments, primary and export production. In situ measurements from augmented CalCOFI and Process cruises will be used to verify and improve algorithms (cf. Kahru et al. 2009). New and biologically relevant algorithms, such as those estimating the relative abundance of different phytoplankton size groups, will be utilized. Of particular interest is the use of MERIS (European Space Agency) data that have 300 m spatial resolution (*cf.* ~1 km of the other ocean color sensors) and are therefore valuable in regions of high mesoscale variability. CCE Associate M. Kahru is PI of a NASA grant to analyze MERIS data specifically in the California Current. Individual mesoscale eddies will be followed using all-weather sea-surface height data. Their biological dynamics will be monitored with ocean color algorithms. Automated objective methods of front detection will be used (Cayula and Cornillon 1992; Kahru et al. 1995; Belkin and O'Reilly 2009).

Sta. M Deep-sea Observatory (www.mbari.org/pelagic-benthic/deepsea.htm): The deep-sea benthic program run by CCE Associate Ken Smith at MBARI has recorded organic carbon fluxes to the deep-sea and its utilization by the benthic macrofauna for over 16 years. Smith and co-workers continuously monitor the flux of sinking particulate matter through the benthic boundary layer, employing time-lapse photography to record benthic processes, and make seasonal measurements of particulate, suspended, and dissolved organic and inorganic fractions through the water column and in the sediments as an estimate of potential food supply to the benthos (Smith et al. 2009). They also monitor sediment community oxygen consumption as an estimate of food consumption by the benthic community.

Discrete Measurements - Quarterly Augmented CalCOFI Cruises

CalCOFI cruises sample a grid of 66 stations (Fig. 2-15) four times per year. CalCOFI focuses on hydrography, inorganic nutrients, phytoplankton biomass (as Chl *a*), and zooplankton biomass; our colleagues at the Southwest Fisheries Science Center assess pelagic fish by enumeration of fish eggs and larvae. Over the last six years CCE has complemented this work through additional measurements that characterize the food web and biogeochemical system, including dissolved organic carbon and nitrogen, microbial populations, phyto- and zooplankton taxa, seabirds, and marine mammals. These combined measurements constitute an unprecedented, detailed, long-term characterization of a marine ecosystem.

CalCOFI and CCE measurements carried out on a regular basis are detailed in Fig. 2-19, where they are also compared to corresponding measurements made at the ocean time series stations HOT and BATS. Differences among the observing programs reflect the different objectives of the programs; studies of populations and ecosystems in the case of the LTER program and biogeochemistry in the case of the ocean time series stations, although there is very substantial overlap among measurements. Augmented CalCOFI measurements are either made at discrete stations or during transit. On station, for the core

CalCOFI measurements, CTD rosettes provide depth profiles of temperature, conductivity, oxygen, Chl *a* fluorescence, 660 nm transmission and PAR. Water samples are taken from up to 20 depths for the analyses of salinity, oxygen, most major nutrients (PO_4, $Si(OH)_4$, NO_3, NO_2) and Chl *a*. Discrete pH and carbonate system variables are measured at selected stations, as well as continuous flow-through pCO_2 and pH. Primary production is estimated at one station per day. Mesozooplankton are sampled with oblique tows from 210 m to the surface using 505-µm mesh nets and with vertical tows on half of the stations, using 202-µm mesh nets. Scientists from the Southwest Fisheries Science Center (SWFSC) determine the abundance of pelagic fish eggs on station and while steaming and enumerate larvae of numerous species of fish from samples collected in plankton nets. Detailed methodologies for CalCOFI measurements are described at swfsc.noaa.gov, calcofi.org and in CalCOFI Data Reports archived at that site. Samples are also taken for special projects, e.g., to characterize microbial diversity using deep 454 sequencing (Huse et al. 2008) in collaboration with the Mirada project (Fig. 2-14), and fish trawling.

The CCE-LTER time series program associated with CalCOFI provides an important space-resolving time series for our site, through the measurements listed in Fig. 2-19. These measurements also cover the five LTER core areas: 1) primary production – direct measurement, 2) distribution and abundance of key populations – measurement in time and space of populations ranging from bacteria to marine mammals, 3) organic matter – particulate and dissolved organic carbon and nitrogen, 4) nutrients – direct measurements of inorganic nutrients, and 5) effects of disturbance – time series of system state and its response to basin-wide forcing and changing human use.

CCE Modeling Studies

Ocean and Atmosphere Circulation Models**:** We will continue to develop the ocean bio-physical modeling frameworks for CCE-LTER. The physical circulation model is the Regional Ocean Modeling System (ROMS) (Haidvogel et al. 2008), with multiple configurations for the CCS. The primary model domain for analysis of decadal trends and inter-decadal variability spans the entire central and eastern North Pacific between 180°-110°W, 20°-62°N (Fig. 2-7A). This ~10 km computational grid is eddy resolving in the horizontal with 40 vertical terrain-following layers. The model is forced at the surface by a blended flux product of the US National Center for Environmental Prediction (NCEP) reanalysis and the CCS regional (~20-km resolution) atmospheric hindcast from the Environmental Climate Prediction Center (ECPC) at Scripps for the period 1950-present. The regional hindcast has been performed by downscaling the NCEP reanalysis with Scripps Regional Atmospheric Model (RSM). The model open boundary conditions are provided by the global 10-km ocean hindcast from the Japanese Earth Simulator and the high-resolution version of the Simple Ocean Data Assimilation (SODA) reanalysis. This large-scale domain permits dynamical analysis of transitions between the CCS and neighboring regions as well as comparisons of ecosystem variability between regions (e.g. with the Gulf of Alaska) (Di Lorenzo et al. 2009).

For process studies we will use a 1/30° resolution CCS model, which resolves submesoscale features for eddy process studies. It is forced by high-resolution COAMPS atmospheric fields and lateral boundary conditions provided by the global ocean state estimate of ECCO (Estimating the Circulation and Climate of the Ocean). We will also conduct process studies using a higher-resolution nested version of the ROMS model as well as the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model (Seo et al. 2007), which combines the ROMS and RSM models mentioned above. The high resolution and coupled frameworks allow us to resolve ocean frontal dynamics and their role in driving biological variability.

Ecosystem Models: The ROMS ocean circulation model includes several ecosystem components, and we are actively creating new ecosystem models. The ROMS-NPZD model has been successfully used to model lower trophic levels in the CCS (Powell et al. 2006; Di Lorenzo et al. 2008) and has recently been modified to include iron limitation (Fiechter et al. 2009). Though this model with iron limitation was applied in the northern Gulf of Alaska, increasing evidence suggests regional iron-limited growth within the CCS (Hutchins and Bruland 1998; Bruland et al. 2001). We have recently modified the NEMURO model (Kishi et al. 2007) to include a carbon:chlorophyll module that will improve our ability to quantitatively compare models and data (Li et al. subm.).

A significant thrust in our CCE-LTER ecosystem model development has been the formulation of continuum size-structured plankton models (e.g., Poulin and Franks in press). These new model structures will allow us to simulate detailed changes in plankton communities in response to physical forcings, and give a higher degree of size-resolution for comparison to field data.

In the emergent ecosystem model approach (e.g. Follows et al. 2007), phytoplankton with stochastically determined physiological characteristics are created and allowed to compete for resources in the spatially and temporally varying nutrient environment driven by the physical circulation. The result is a modeled ecosystem with self-selecting, variable phytoplankton communities. Using the 1/10° CCS model framework (Veneziani et al. 2009a), Goebel et al. (submitted) investigated the modeled biodiversity and biogeography of the time-mean fields as well as phytoplankton succession within the CCE (Fig. 2-18). The model included multiple nutrients, 78 phytoplankton organisms divided into 4 functional groups, and 2 zooplankton compartments. The nature of this model thus lends itself to investigations of the physical and biological processes that structure planktonic communities over ecologically relevant time scales. This model will be used to study inter-decadal variability in communities as well as ecosystem processes within and associated with CCS fronts and eddies.

Ocean Inverse Model: The ROMS model also includes an inverse modeling component that uses the Tangent Linear and Adjoint Models of the ocean circulation module (Moore et al. 2004). Several studies conducted by the PIs have used this inverse platform to explore the sensitivity of the physical and biological systems to changes in forcing conditions and upwelling in the CCS (Chhak and Di Lorenzo 2007; Veneziani et al. 2009b; Moore et al. 2009). In support of CCE sea-going activities, the ROMS 4D-variational data assimilation system will be used to assimilate in situ temperature and salinity data from hydrography, SeaSoar observations, glider data, and ADCP upper-ocean currents, along with satellite altimetric estimates of sea level, satellite observations of SST, ocean data from the NOAA buoys, and whatever other data types are available. These fits will attempt to reconstruct the mesoscale circulation observed during cruises, and provide crucial dynamically consistent diagnostics of the circulation for interpreting the interactions among physical, atmospheric and biological dynamics.

Lagrangian and Transport Models: The transport dynamics associated with mesoscale eddies and the CCS mean circulation components (e.g. upwelling cells, the California Undercurrent) are important to the understanding of ecosystem dynamics and their transitions. In order to characterize the advection and transport dynamics we will make use of the ROMS passive tracer (Combes et al. 2009) and Lagrangian (Petersen et al. 2009; Drake and Edwards 2009) module. The passive tracer module has been used the CCS to characterize alongshore connectivity (Rasmussen et al. 2009) and the dynamics of cross-shore exchanges and their relationship to the upwelling cells (Combes et al. in prep).

ISSE – Integrating the natural and human dimensions of the CCE

CCE – Ecosystem Services: The CCE is an integral part of the culture and economy of the Southern California region. Services provided by this ecosystem range from cultural, to provisioning, and regulating. Of these services, coastal climate regulation, commercial fishing, sense of place and recreation are the most important (Fig. 2-21). The rather limited number of interactions among services (Fig. 2-21) reflects the nature of pelagic ecosystems, whose drivers are primarily physical and operate on an ocean-basin or regional scale. Of the ecosystem services listed, coastal climate regulation is the most important since the cold California Current coming from the north and the prevailing westerly winds shape the coastal climate and the ways in which residents of Southern California live and interact with their environment. However, this fundamental ecosystem service is primarily driven by global or basin-scale forcing and, in the short term, is not directly affected by activities of humans living along the coast of Southern California.

Recreational and commercial fisheries supported by the CCE (Fig. 2-22) are strongly dependent both on the human and ecological templates (Hannesson et al. 2006). Important factors are stock abundance and spatial distribution for the ecological template and fisheries management decisions, marginal costs of the fishery and marketability of the catch for the human template. External drivers of the system affect directly or indirectly either template (Fig. 2-22). Short-term pulses, such as ENSO cycles have significant effects on some fisheries such as squid. Long-term presses such as decreasing concentrations of oxygen at depth in the Southern California Bight and perhaps changes in aragonite saturation state are expected to decrease essential habitat of benthic species (e.g. rockfish). Management of rockfish will have to take these long-term trends in habitat area into account. Pacific sardine is one of the few fisheries in the world which is managed based on an environmental index, the sea surface temperature at the Scripps pier, which too is changing over the long-term. Management decisions in turn, particularly those affecting sardine and anchovy, have the potential to affect the biotic structure of the ecosystem, since small pelagic fish, when abundant, can affect plankton biomass, community structure, and nutrient cycling (Fig. 2-22).

CCE – Ongoing Work and Questions: As part of the LTER network-wide Maps and Locals (MALS) initiative, CCE-LTER has begun an investigation of how fishers' behaviors respond to changing ocean climate. The goal of MALS is for each participating LTER site to compile land use maps for multiple points in time for its site, and then to characterize the changes over time, both quantitatively and qualitatively. We are focusing on ENSO cycles and large-scale shifts in system state (e.g. PDO) and will construct sea-use maps for several points in time. We propose to extend this line of inquiry over the next six years and address two questions: 1. How do fishers change their behavior in response to scientific knowledge and uncertainty (e.g., predictions of El Niños)? 2. What are the potential impacts of ocean acidification on fisheries and mariculture, and on human decisions in the face of this source of environmental change? Over the next 6 years we will primarily focus on the first question, Q5 in our ISSE loop diagram (Fig. 2-22), and pursue the second question using support sought from other sources.

Proposed Work: The Impact of Climate Change on Fishery Production and Fishers' Response. In the second phase of CCE we propose to study the link between fisheries and climate (Fig. 2-23), which remains poorly understood due to theoretical and empirical challenges. We will use for this study the unique data sets of the CalCOFI and CCE-LTER programs and recently developed econometric methods (Fig. 2-23). The major challenges faced are: 1) The climate-ocean-fishery interaction must be viewed as a coupled nonlinear dynamic system where small disturbances may result in large structural changes. Traditional models, including the reduced form model cannot handle such nonlinearities, including significant regime shifts. A structural bioeconomic model will be more useful in this case. 2) Fishers adapt to climate variability through widening spatial searching and technological innovation, which offsets the impact of climate change. Ignoring such behavioral responses may lead to a biased estimate of the impact (M. Smith et al. 2006; 2008; Zhang 2009). However, if the targeted resource population redistributes beyond the accessible boundary or political boundary, fishers may face larger adverse impacts. Analysis of the adaptive behaviors of fishers requires a spatially explicit model. 3) Climate change affects fishery production through altered abundance as well as spatial distribution. However, fish abundance information is not always available at fine spatial and temporal scales. This problem will be dealt with using recently developed approaches based on fishery dependent information, e.g., catch and effort data, to infer fish stocks (Zhang and Smith in press).

We will first address all three challenges in our study using Pacific sardine as an empirical case study, and later include other fisheries. Pacific sardine is a perfect case because: 1) The sardine-climate connection has been well documented (Norton and Mason 2005; Herrick et al. 2007). Empirical studies have found that California sardine landings are correlated with accumulated anomalies of physical indices. 2) The sardine data set has been well maintained. The aggregated data consist of a long time series to study the climate change effect. The disaggregated data have adequate spatial resolution to study fishers' behavioral response. 3) There are extant fishery management policies for Pacific sardine because of its collapse and renewal over the last decades.

This research will be conducted by a resource economist (J. Zhang) collaborating with CCE scientists and the NOAA/NMFS Southwest Fisheries Science Center.

Regionalization, Cross-Site, and Collaborative Studies

Linkages to other LTER sites

We have found the EcoTrends project to be a very inclusive forum for cross-site analysis. CCE has been active in the editorial board for EcoTrends from its inception and has co-written the climate chapter. We will continue to contribute to the development of the EcoTrends web site and foster cross-site comparisons. We are working with others in the State Changes working group on 2 manuscripts that compare several LTER sites with respect to propensity for abrupt changes in community composition.

CCE has a natural connection to SBC, as the source of ocean forcing that influences their kelp forest site. We have already had a series of exchanges with SBC scientists and graduate students and will expand these in the future. CCE has co-written a children's book (Sea Secrets) with PAL, and expects to conduct comparative work related to biogeochemical cycles and krill life histories in the coming review cycle.

CCE looks forward to teaming with other sites to further advance the ISSE framework, particularly in relation to 1) harvesting (fishing) and 2) ocean acidification (OA). With respect to OA, the California Current upwelling system has already been shown to be subject to corrosive waters undersaturated with respect to aragonite (Feely et al. 2008). A new marine chemist (T. Martz) with interest and expertise in the marine chemistry of OA has joined CCE. We know this topic is of considerable interest to colleagues at MCR, PAL, and SBC, and to some at FCE, GCE, VCR, and PIE. We anticipate developing a coordinated program with other interested sites that exploits the diversity of biomes and differences in susceptibility of human populations to OA within the LTER network.

CCE is a collaborator in the MALS (Maps and Locals) project, together with 10 other LTER sites, to document spatially-explicit changes in habitat use over time. A CCE scientist and a newly recruited economist (J. Zhang) will continue to work in association with others across the network. CCE is one of 13 LTER sites collaboratin in the MIRADA (Microbial Inventory Research Across Diverse Aquatic LTERs) effort, led by L. Amaral-Zettler and coordinated for CCE by B. Palenik. MIRADA uses massively-parallel, 454-based rDNA tag sequencing to characterize microbial diversity. We also look forward to expanding interactions with others in the LTER network.

Linkages to other Programs

CCE is closely associated with CalCOFI (the *California Cooperative Oceanic Fisheries Investigations*), now in its 61st year and one of the most important ocean time-series programs. We have added a suite of measurements to CalCOFI, primarily microbial and biogeochemical variables, that also help to relate our coastal upwelling ecosystem with ocean measurements made in the central North Pacific Gyre at HOT, the subtropical Atlantic at BATS, the southern Caribbean at CARIACO, and elsewhere. We expect to expand cross-ecosystem comparisons with these and other ocean programs.

CCE, via CalCOFI, is part of PACOOS (the Pacific Coast Ocean Observing System), a federated series of ocean observing locations in the California Current System along the U.S. west coast, with international links to Canada and Mexico. In addition to contributing measurements, CCE scientists and IM people have played an active role in organizing PACOOS data sharing demonstration projects and will continue to do so. While the U.S. OOI (Ocean Observing System) is allocating most of it assets in the California Current System off the coast of Oregon, through PACOOS and other programs we expect to link CCE to the upstream and downstream programs in OOI in order to develop a more coordinated series of coast-wide ocean measurements and models.

Through CCE co-PI R. Goericke, CCE is a collaborator in SCCOOS (the Southern California Coastal Ocean Observing System), which is a science-based decision support system to provide local, state, and federal agencies, as well as the general public, with the information necessary to manage and sustain coastal habitats and resources.

PI M. Ohman is also on the advisory board for an IGERT program based at SIO concerning Global Change, Marine Ecosystems and Society, whose theme interdigitates well with the CCE-LTER site.

Our collaboration with Ken Smith's deep-sea benthic flux program (Sta. M), is a unique linkage between pelagic ecologists studying food web/climate interactions in the upper ocean and deep sea-floor studies of the pathways and utilization of organic matter flux. These collaborations will continue to expand.

International collaborations

CCE currently has active collaborations with a modeling group in France, fisheries oceanographers in Japan, an optical oceanographer in Norway, machine learning specialists in France, Information Management experts in Finland, and others. We see every sign of these collaborations expanding.

Synthesis

The California Current Ecosystem LTER site is emerging as a center of process-oriented understanding of the dynamics of a major coastal upwelling ecosystem and the mechanisms underlying ecosystem state transitions. With this renewal, the CCE site is now poised to develop a deeper understanding of the California Current pelagic ecosystem, and of processes leading either to abrupt transitions or ecosystem resilience in ocean communities. These advances are made possible through the confluence of several site characteristics, including:

- The benefits of 60 years of (ongoing) ocean observations that enable us to characterize ecologically important types of ecosystem variability and the underlying forcing mechanisms.
- Experimentally oriented process studies that focus on key mechanisms of stratification and nutrient supply, and their perturbations by mesoscale fronts and eddies.
- A multi-layered modeling approach that explores processes conceptually and then implements key biotic and physical processes in realistic eddy-resolving simulations coupled to 4-D ocean circulation.
- Contemporary observational technologies, including robotic ocean gliders, a Moving Vessel Profiler, Lagrangian experimental drift arrays, and remote sensing tools.
- A newly developed study at the interface of human and natural systems that will understand how human harvesting decisions interact with environmental uncertainty.
- A unique interdisciplinary team of scientists, graduate students, and other personnel.

Our site has already developed hindcast models that enable us to understand historical processes that have influenced this ecosystem in the past and, in one case, developed a successful short-term forecast of ocean upwelling. We expect to make further inroads into the realm of ecosystem forecasting in this next grant cycle. These developments should be of immediate interest and relevance to other pelagic-influenced biomes, including polar pelagic, nearshore kelp forest, and temperate and polar lake systems. These studies also provide an important contrast to highly structured benthic habitats such as coral reefs and estuarine systems, and many terrestrial biomes. But beyond the immediate connection with other marine LTER sites, we expect our results to be of broader applicability to ecologists in a number of arenas. These include those interested in the:

- relative roles of predation and physically-mediated resource supply in structuring food webs;
- mechanisms leading to ecological state changes and, conversely, to ecological resilience;
- effects of large scale climate drivers (e.g., ENSO, NPGO, PDO) on local ecosystem dynamics;
- mechanisms by which disturbance regimes alter nutrient fluxes and predator-prey interactions;
- the effects of climate change in altering ecological disturbance regimes;
- the interactions of human harvesting decisions with environmental uncertainty.

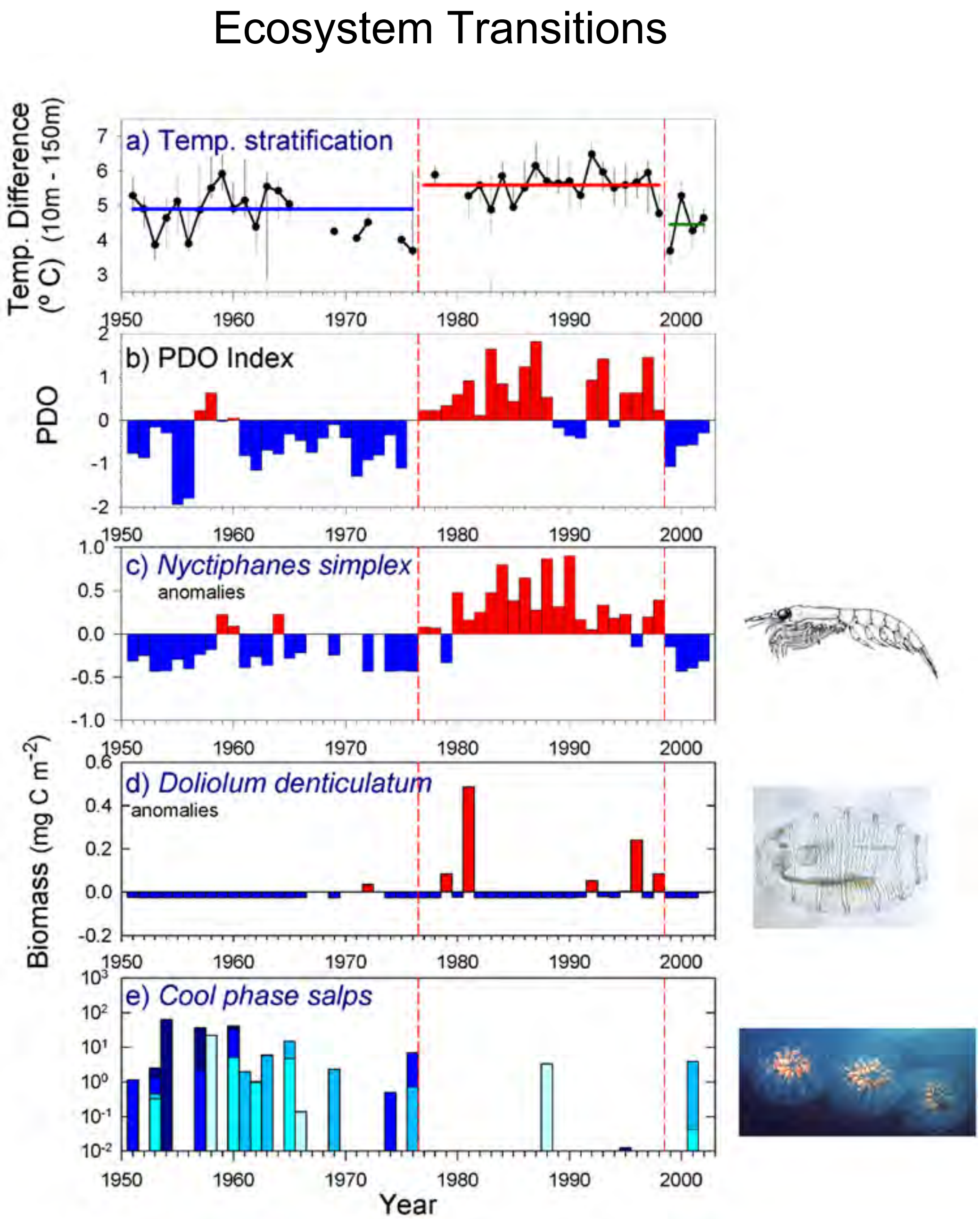

Fig. 2-1. Long term variability in the CCE-LTER region, illustrating one type of abrupt transition in ecosystem state (vertical lines in 1977 and 1999). a) Springtime temperature stratification in the California Current, from CalCOFI lines 80-93, b) Annual averages of the Pacific Decadal Oscillation Index (Mantua et al. 1997), c) Anomalies of biomass of the euphausiid *Nyctiphanes simplex*, d) Anomalies of biomass of the doliolid *Doliolum denticulatum*, e) biomass of one assemblage of salps. (Ohman and Venrick 2003).

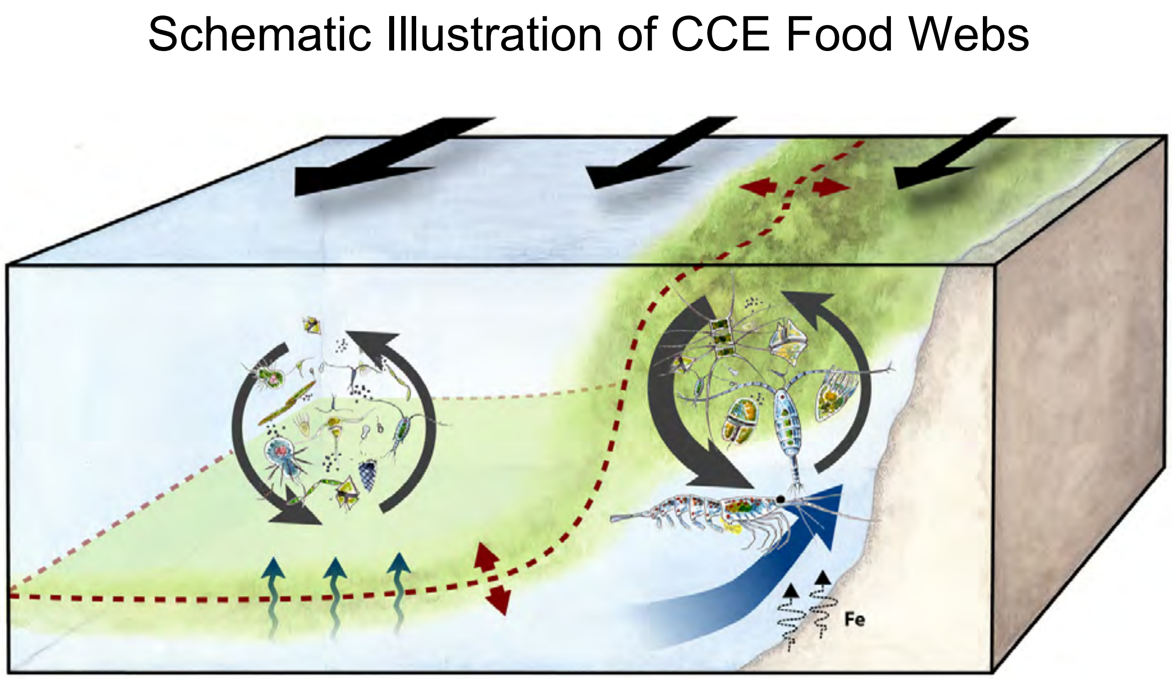

Fig. 2-2. Conceptual diagram of general spatial distributions and food-web relationships associated with wind-driven upwelling processes in the CCE study region. Bold upper arrows depict the onshore-to-offshore gradient in equatorward wind stress at the sea surface. Large blue arrow represents upwelling at the coastal boundary. Small blue arrows represent upwelling in the offshore region due to wind stress curl. Red arrows are indicative of onshore-offshore and vertical movements of the nitracline. Circular arrows depict relative magnitudes and balance of phytoplankton growth and grazing loss processes in eutrophic and oligotrophic food webs, dominated by large and small plankton, respectively (M. Landry and K. Carlson)

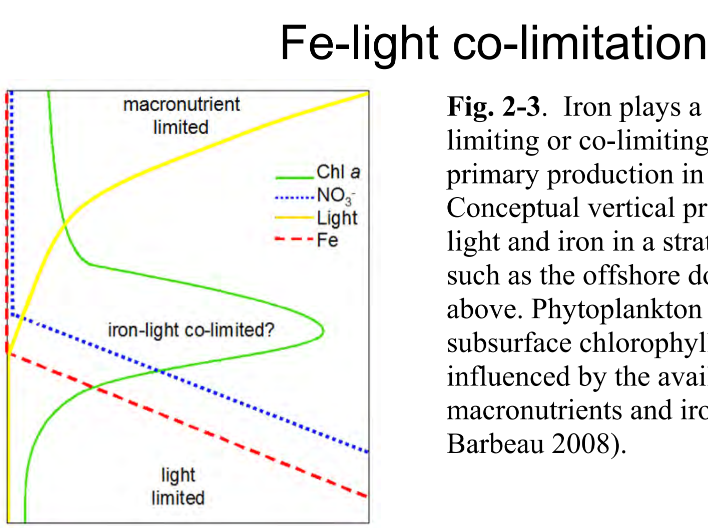

Fig. 2-3. Iron plays a significant role as a limiting or co-limiting micronutrient for primary production in the CCE study area. Conceptual vertical profiles of Chl *a*, nitrate, light and iron in a stratified oceanic system, such as the offshore domain in the panel above. Phytoplankton communities at the subsurface chlorophyll maximum are influenced by the availability of light, macronutrients and iron (cf. Hopkinson and Barbeau 2008).

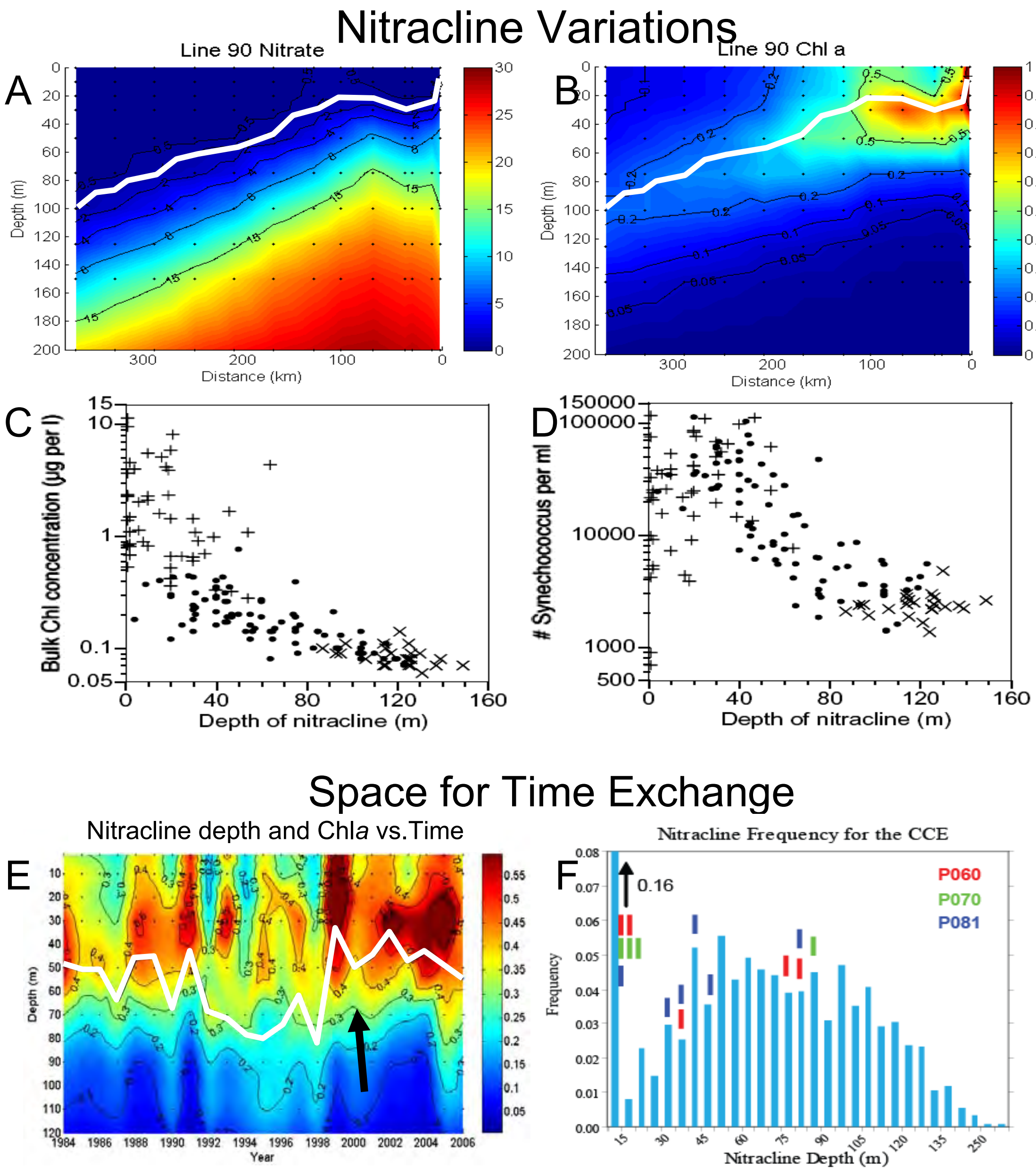

Fig. 2-4. **Nitracline Variations in Space**: Nitracline depth (NCD: where NO_3 reaches 1 µM) in the CCE region. (**A**) NCD (white line) increases with distance from shore. Biological properties often covary with NCD, e.g., (**B**) Chl *a* (contours) and NCD (white line). Standing stocks of (**C**) surface Chl *a* and (**D**) abundance of the cyanobacteria *Synechococcus* spp. covary with NCD (**C,D** from Collier & Palenik 2003; all data from CalCOFI cruises).

Nitracline Variations in Time: Within the CCS, NCD (**E**, white line) varies significantly from year-to-year. Chl *a* standing stocks (**E,** contours**)** strongly responded to changes in NCD that were associated with the 1998/99 shift in the PDO (black arrow). These data illustrate that relationships between biological properties and NCD along spatial gradients in (**B**) are similar to such relationships observed over time (**E**). The substitution of space for time is a central tenet of our Process Cruise work. To date we have covered three distinct types of NDCs (**F**), where NCDs observed during our Process Cruise experiments (red, green, dark blue bars) are superimposed on a frequency distribution of NCDs across our study area (pale blue bars).

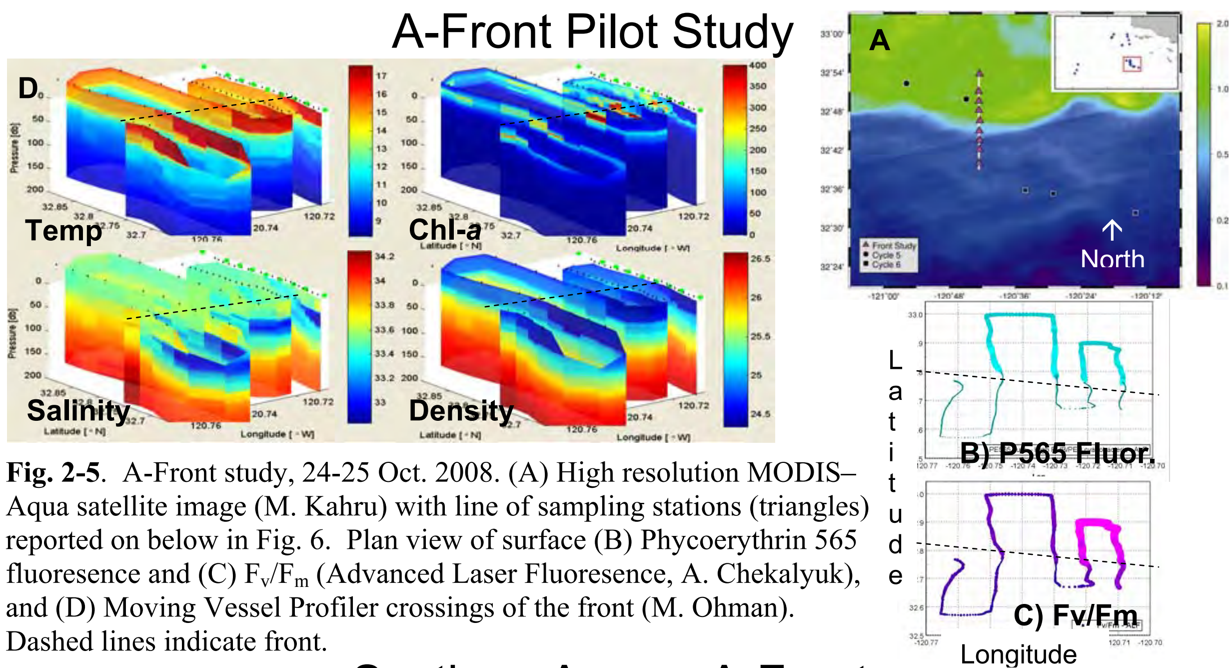

Fig. 2-5. A-Front study, 24-25 Oct. 2008. (A) High resolution MODIS–Aqua satellite image (M. Kahru) with line of sampling stations (triangles) reported on below in Fig. 6. Plan view of surface (B) Phycoerythrin 565 fluoresence and (C) F_v/F_m (Advanced Laser Fluoresence, A. Chekalyuk), and (D) Moving Vessel Profiler crossings of the front (M. Ohman). Dashed lines indicate front.

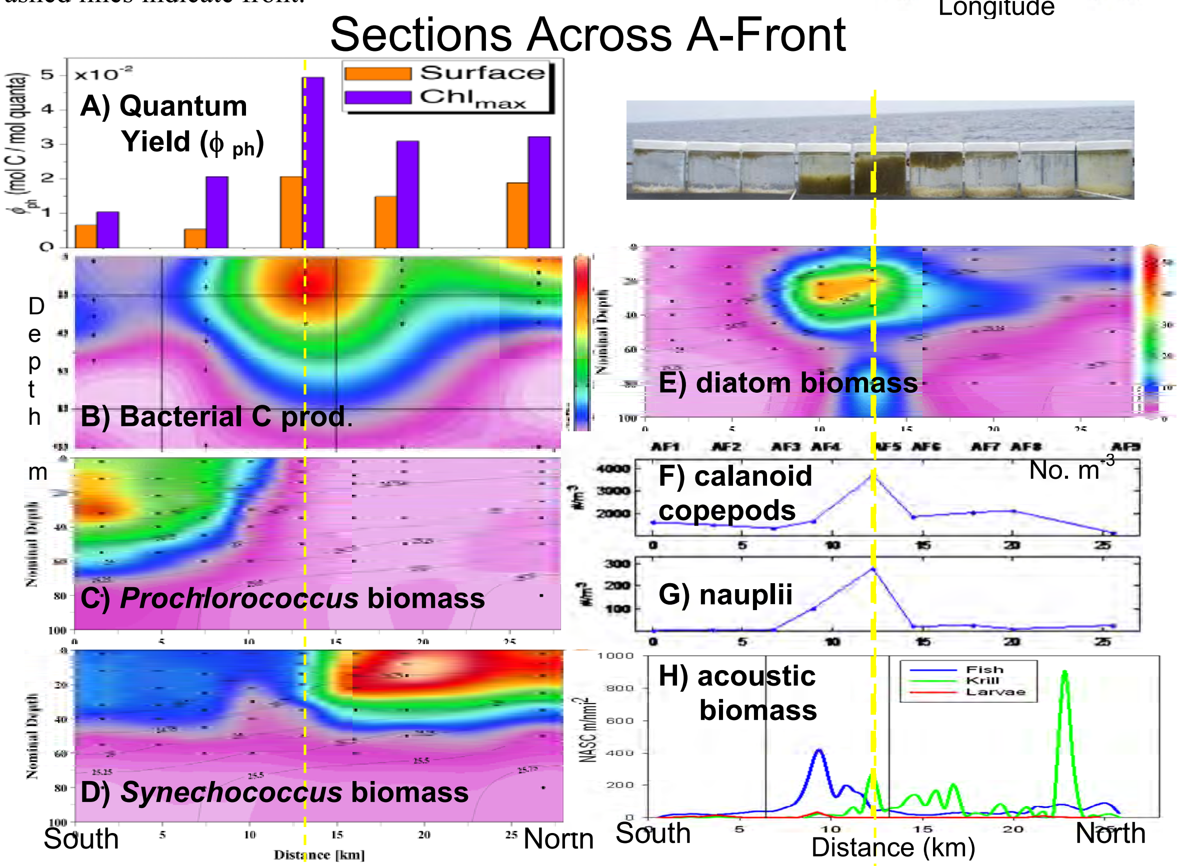

Fig. 2-6. Changes in properties in a line of stations across the A-Front (dashed line), Oct. 2008. (A) Photosynthetic quantum yield ϕ_{ph} (H. Wang, G. Mitchell), (B) Bacterial carbon production (T. Samo, F. Azam), (C) *Prochlorococcus,* (D) *Synechococcus*, and (E) total diatom C biomass (A. Taylor, M. Landry); abundance of (F) calanoid copepods and (G) total nauplii (M. Ohman), and (H) acoustic estimates of fish (blue), krill (green), and larvae (red) (A. Lara-Lopez and T. Koslow). Photo in upper right indicates composition of 202-µm net tows, sampled across the front.

Schematic Ocean Circulation on 3 Spatial Scales

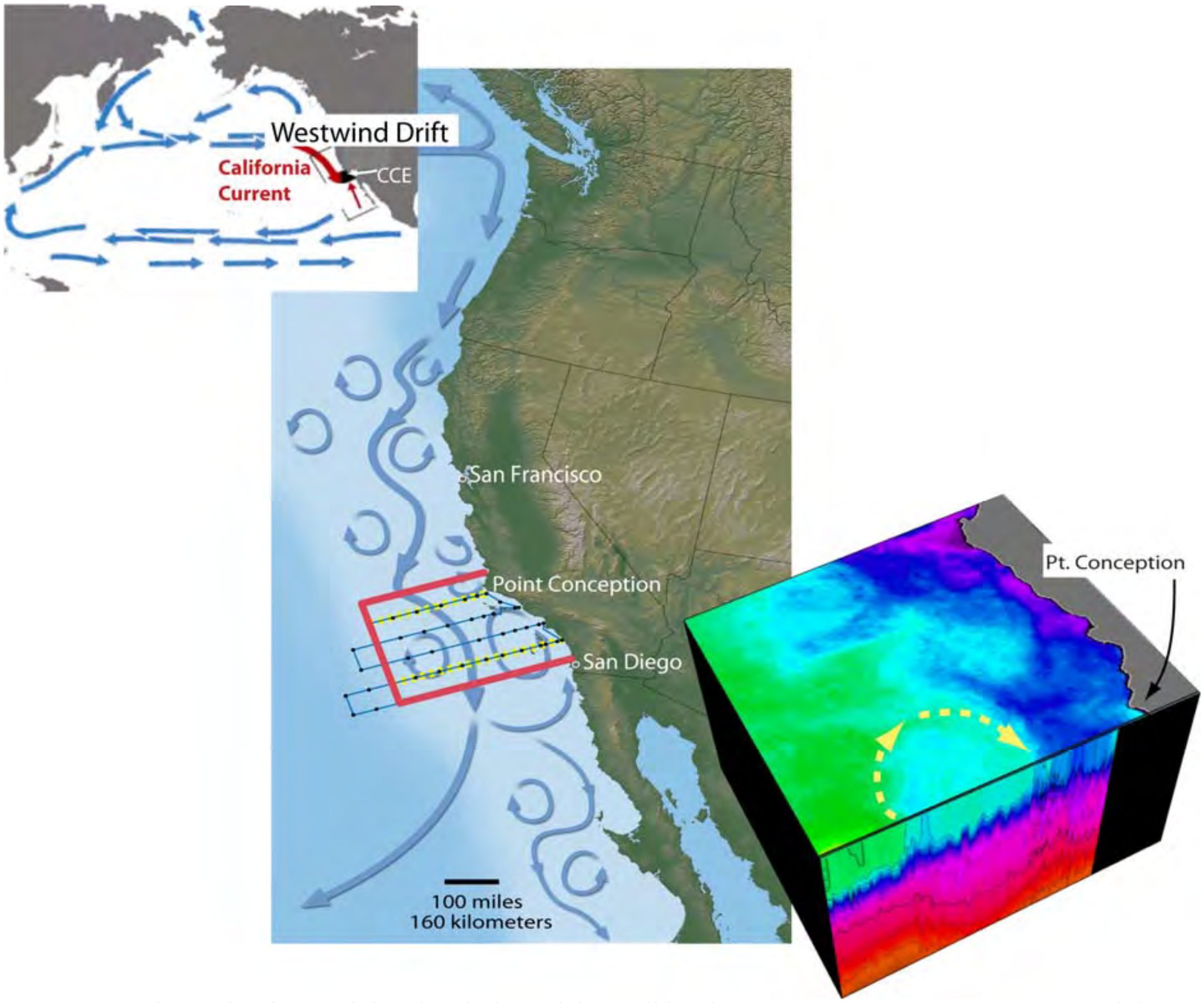

Fig. 2-7. Schematic views of the circulation of the California Current System (CCS) on 3 spatial scales: (top) Basin Scale, (middle) Regional Scale and (bottom) Mesoscale.

At the **basin** scale, the CCS forms the eastern boundary current of the Subtropical Gyre in the North Pacific. It is fed by the southward bifurcation of the Westwind Drift in the north and feeds the North Equatorial Current to the south.

Regionally, the CCS includes the equatorward California Current, which slowly and broadly meanders through a field of vigorous eddies that are spawned by instabilities of the current, topographic/coastline forcing and local wind forcing. Closer to shore, strong coastal upwelling frontal flows, which are driven by seasonal northerly winds, also contribute to the unstable eddy field. The Southern California Eddy, centered over the Southern California Bight, frequently provides a recirculation feature in the CCE region. The subsurface California Undercurrent near the shelf break (thin red arrow in upper plot) and the seasonal nearshore Davidson surface current (not shown) constitute regional poleward flows.

On the **mesoscale**, a slice through an observed anticyclonic mesoscale eddy, offshore of Point Conception, reveals associated fronts that extend through the surface mixed layer and advect water properties along a circulation pattern indicated by the yellow-dashed arrow. This is a composite of a satellite-derived AVHRR sea surface temperature map and a subsurface temperature section from a *Spray* ocean glider.

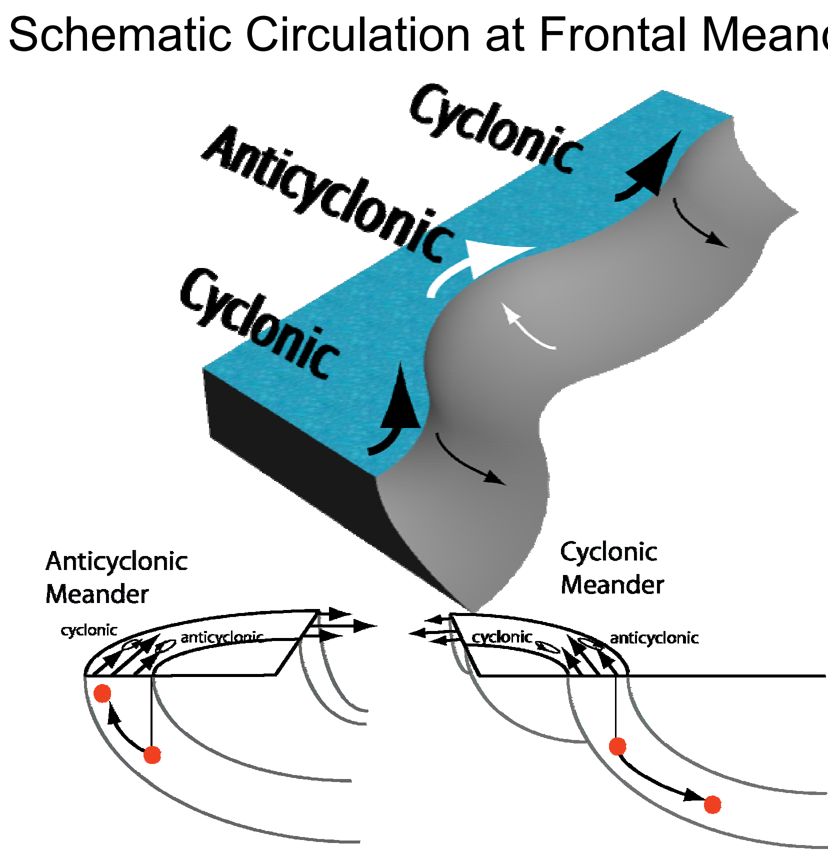

Fig. 2-8. Schematic of the vertical and horizontal circulations at frontal meanders. In an anticyclonic meander the conservation of potential vorticity causes upwelling of water along isopycnals at the front (left orange dots). Downwelling occurs in cyclonic meanders of the front (right orange dots).

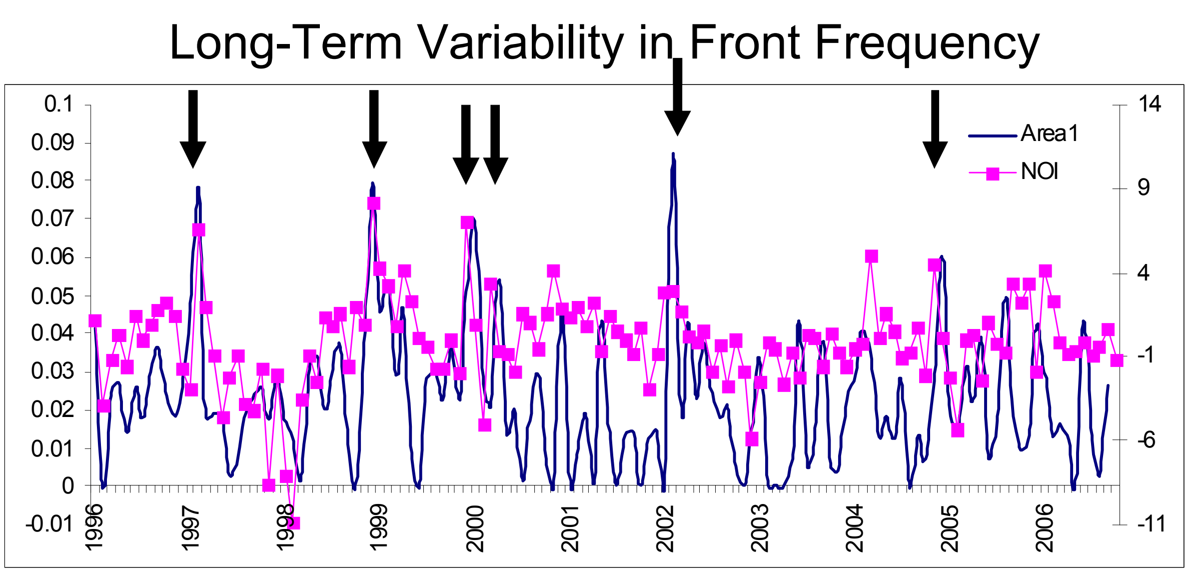

Fig. 2-9. Front frequency in the Southern California Bight (dark blue line) vs. Northern Oscillation Index (magenta line, Kahru and Manzano in prep.). Arrows indicate coincident peaks.

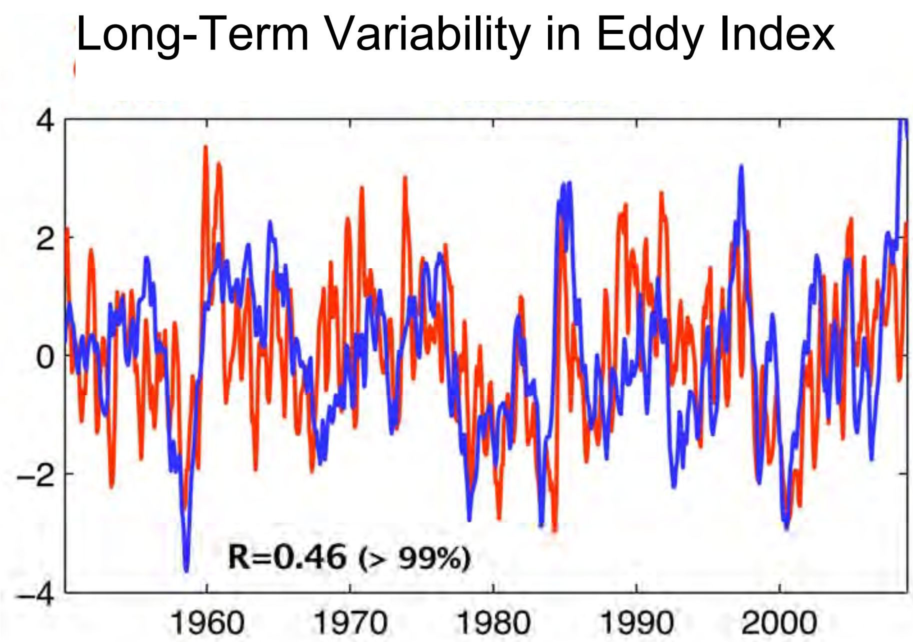

Fig. 2-10. Long-term changes in q, a measure of the intensity of mesoscale activity in the CCE region. Red: measured changes in mesoscale activity derived from ROMS model hindcasts. Blue: predicted changes in q. Predictions of q are based on a linear time-filtering of the wind-stress curl gradient, showing that interannual and decadal changes in the intensity of mesoscale dynamics in the CCE region are strongly controlled by the wind (Di Lorenzo et al. in prep.).

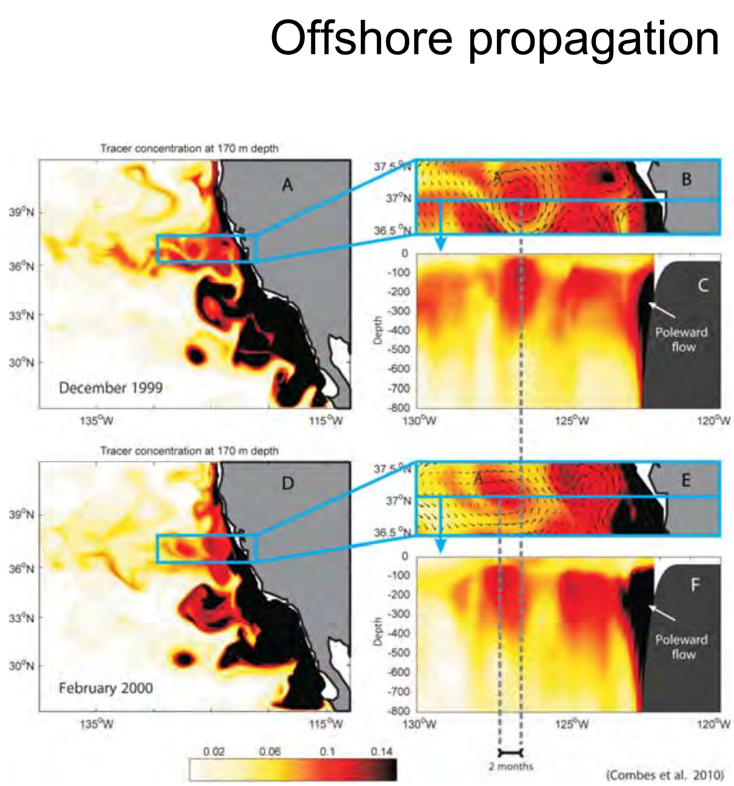

Fig. 2-11. Simulation of eddy-driven westward transport of an inert tracer injected continuously into the CA Undercurrent, off Baja and the Southern CA Bight. Bottom panels are 2 months after the top panels. **A, D**: Tracer concentration at 170 m. **B,E**: Blow-up of tracer in region off Monterey Bay shown in panels A, D. Arrows show current vectors, and a cyclonic eddy (A) is highlighted. Note the westward movement of the eddy over the 2 months. **C, F**: Vertical section through panels B, E showing high tracer concentrations in the cyclonic eddy, and in the northward-flowing undercurrent. This simulation demonstrates the northward transport of properties in the undercurrent, and the westward advection of those properties in mesoscale features (Combes et al. in prep.).

Changes in Chl-*a* as Eddies Age

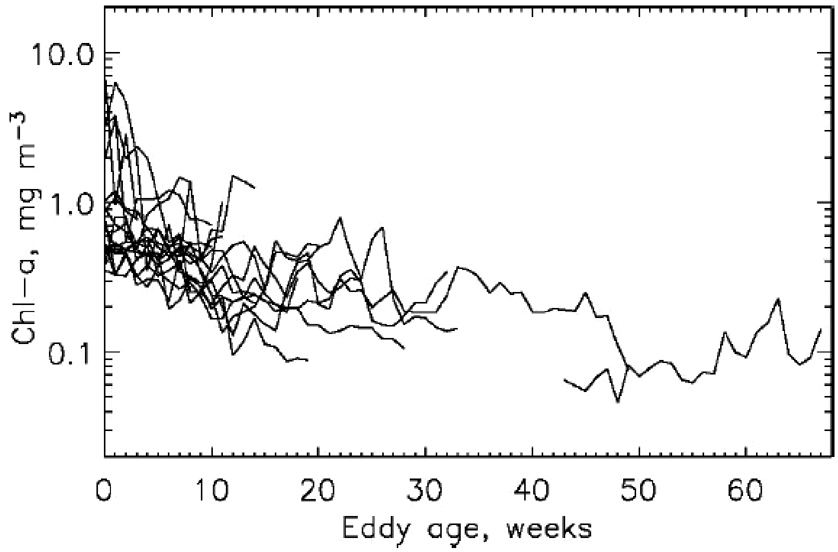

Fig. 2-12. Decrease in Chl *a* concentration in cyclonic eddies as they age, while traveling westward from the California coast, passing through the Sta. M area (M. Kahru unpubl.)

Control Volume Property Fluxes

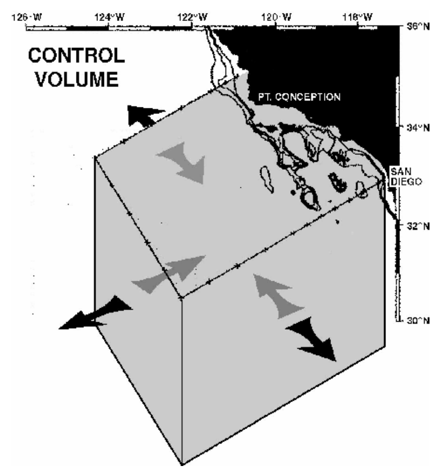

Fig. 2-13. 3-D Control Volume for the CCE region. Assuming geostrophic convergence into the box is balanced by Ekman divergence out of the box, the net flux of nutrients and other properties in the CCE region can be calculated.

Spatial Changes in Microbial Communities

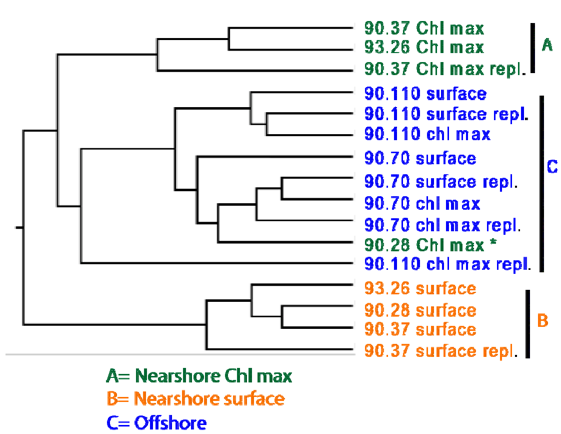

Fig. 2-14. Cluster diagram of samples from the CCE region based on a comparison of their eukaryotic 18S rRNA diversity (Bray-Curtis distances and UPGMA tree). This diversity was assayed using deep 454 sequencing (Huse et al 2008) in collaboration with the MIRADA project. Nearshore (stations 90.37, 90.28 and 93.26) surface samples clustered together as did some nearshore chlorophyll max samples (90.37, 93.26). Open ocean samples tended to cluster regardless of depth. The details can vary slightly if bacterial 454 sequences are used to cluster the samples (not shown). B. Palenik unpubl.

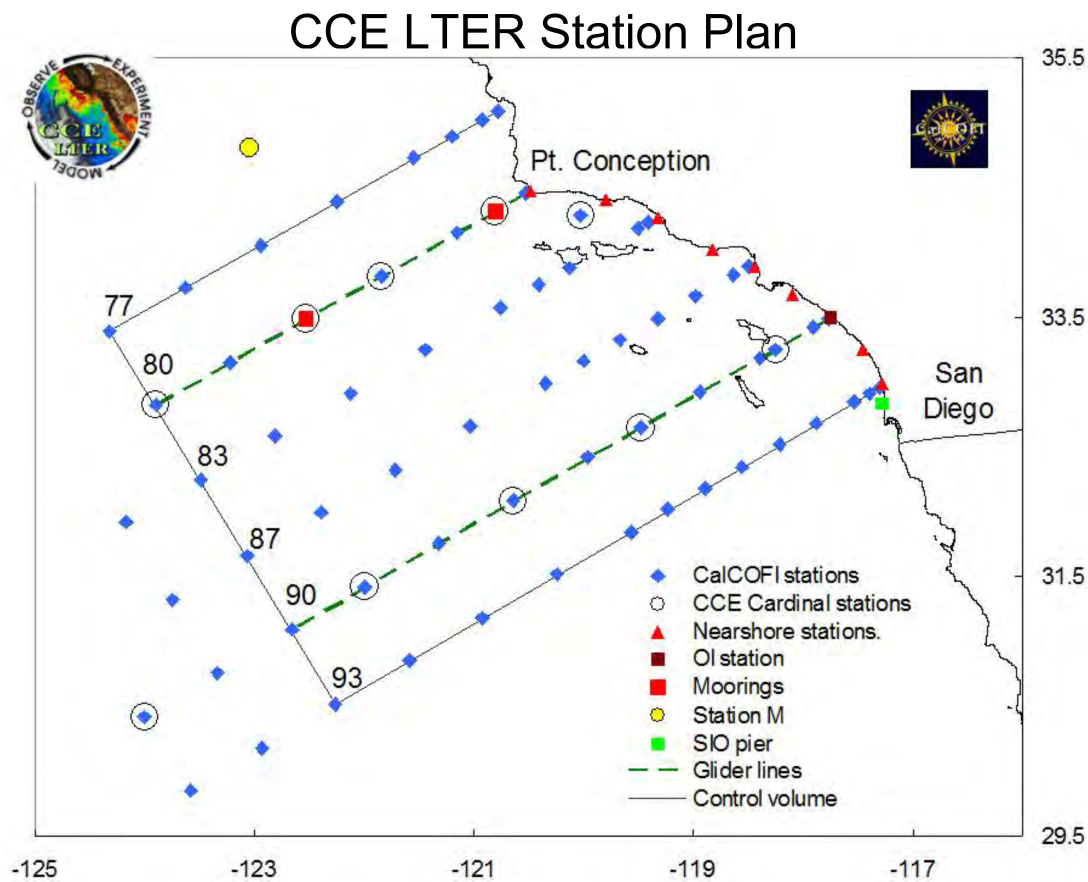

Fig. 2-15. Sampling pattern for CCE-LTER, CalCOFI, and related programs. CalCOFI lines are labeled with their numbers, 77 to 93.

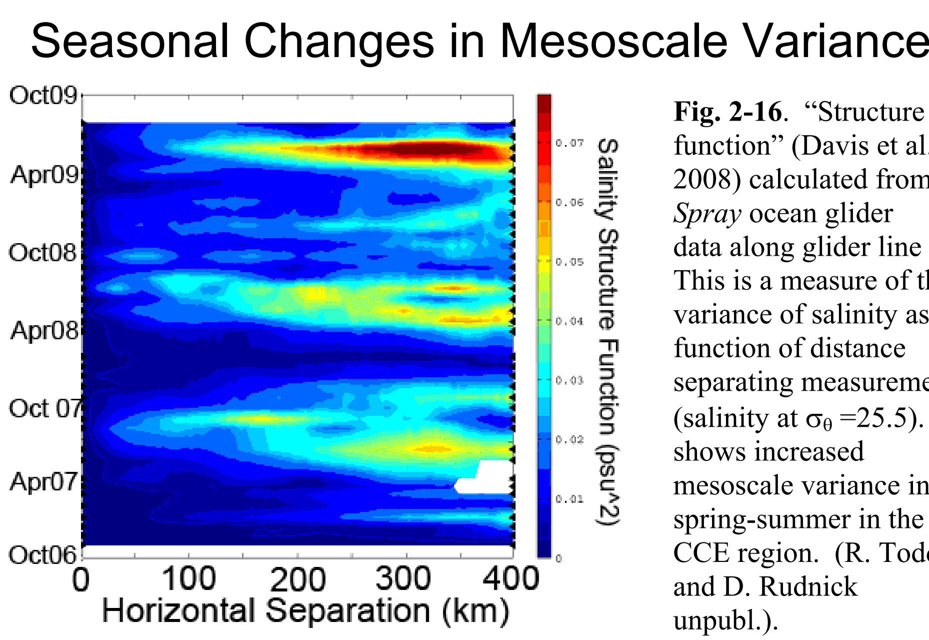

Fig. 2-16. "Structure function" (Davis et al. 2008) calculated from *Spray* ocean glider data along glider line 90. This is a measure of the variance of salinity as a function of distance separating measurements (salinity at σ_θ =25.5). It shows increased mesoscale variance in spring-summer in the CCE region. (R. Todd and D. Rudnick unpubl.).

Schematic of Sampling Plan Along Frontal Meanders

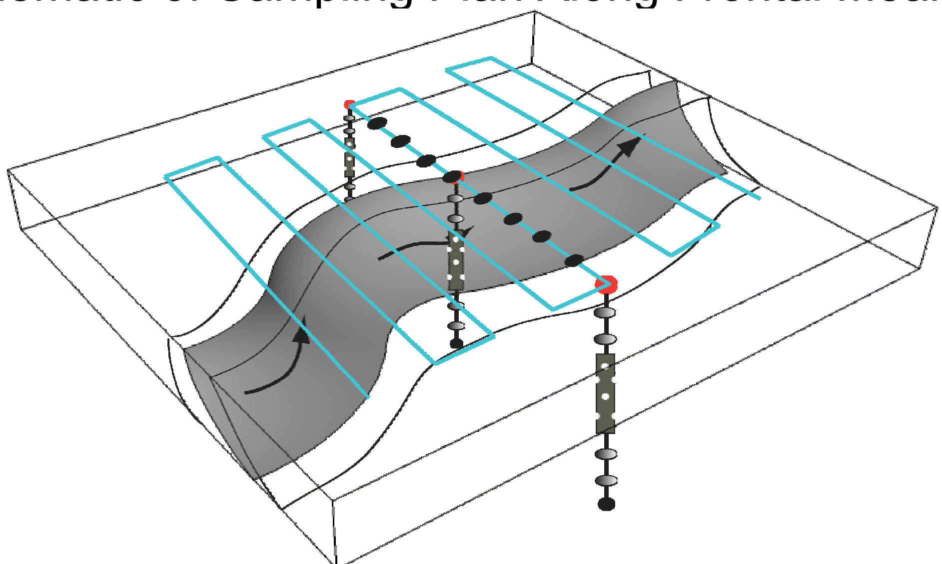

Fig. 2-17. Schematic of the sampling scheme across a frontal meander. The front is depicted by the gray surface, with two flanking isopycnal surfaces shown with black lines. The ship towing the SeaSoar will survey the front by following a "radiator" pattern (blue lines) with long legs approximately orthogonal to the front. Drift arrays (orange floats with drogues at 15 m and incubation bags at multiple light depths through the euphotic zone) will be released in the front, and on either side of the front at distances far enough away to sample waters unperturbed by the front. (Not to scale)

Emergent Ecosystem or "Darwin" Model

Fig. 2-18. Five-year average distributions of the dominant plankters remaining in a run of the "Darwin model" (cf. Follows et al. 2007). From a suite of 78 stochastically parameterized phytoplankton divided among 4 functional groups, selection by the environment, competition, and grazing mortality led to the final distributions (Goebel et al. submitted). Diatoms were abundant near the coast, while large non-diatom phytoplankton were found farther offshore and to the south of the domain. Offshore waters were dominated by smaller eukaryotic and prokaryotic phytoplankton. Microzooplankton biomass was highest offshore and to the south, while the larger mesozooplankton were concentrated near the coast where they grazed on larger phytoplankton and microzooplankton.

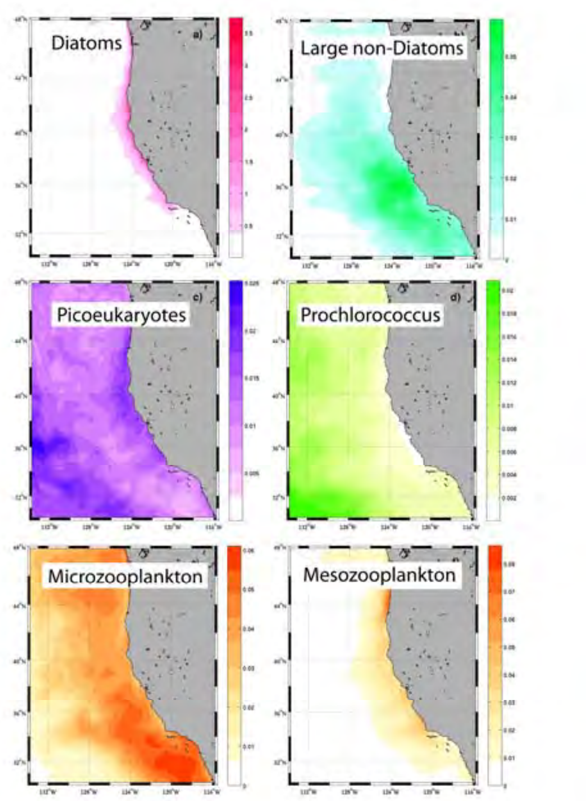

Fig. 2-19. Comparison of variables measured in CCE/CalCOFI and core measurements of the HOT and BATS time-series programs. Measurements added to CalCOFI by CCE are shown in RED font. Biological stock and rate measurements made only on the CCE Process cruises are not listed.

Variable	CalCOFI-Core/CCE-Augmented	HOT & BATS	CCE Process Work
Physical Environment			
Temperature, salinity, pressure	CTD profile, continuous surface	Yes	Yes, plus MVP
Salinity, bottle	salinometer	Yes	Yes
Irradiance, daily PAR	CTD & ship MET, PAR sensors	Yes	Yes
Light transmission	Transmissometer, 660 nm (CTD)	Yes	Yes
Bio-optics – spectral	No	HOT only	Yes
Upper ocean currents	Hydrography, gliders, & ADCP	HOT only (ADCP)	Yes
Biogeochemistry – Elemental Stocks & Rates			
Dissolved oxygen, profile	Oxygen sensor, CTD	Yes	Yes
Dissolved oxygen, discrete	Microwinkler	Yes	No
Sea-surface pCO_2, underway	IR absorbance (MBARI, PMEL)	Yes	No
Sea-surface pH, underway	Electrode (Martz)	No	No
Total CO_2, discrete	Coulometry Yes		No
Alkalinity, discrete	Gran titration	Yes	No
pH, discrete samples	Calculated	Spectrophotometry	No
NO_3, NO_2, PO_4, $Si(OH)_4$	Autoanalyzer	Yes, low-level N, P	Yes
Nitrate, continuous	ISUS sensor, CTD (Goericke) No		No
Ammonium	Autoanalyzer No		Yes
Dissolved iron	No	No	FeLume flow injection
Dissolved organics (DOC, DON)	High-temp oxidation (Aluwihare)	Yes Yes	
Suspended particulate C, N	Dry combustion (Aluwihare) Yes		Yes
Suspended particulate P	No	HOT only	No
Particulate biogenic Si	No	Colorometric	Colorometric
Primary production (POC)	^{14}C uptake – deck	*In situ*	*In situ*
Primary production (DOC)	^{14}C uptake – deck (Goericke)	*In situ*	*In situ*
Bacterial production	No	^{3}H-leucine, thymidine	Yes
Export – particulate C, N, mass	No	Sediment trap	Sediment trap, ^{234}Th
Export – particulate P	No	HOT only	No
Export – particulate biogenic Si	No	Sediment trap	Sediment trap
Mesozooplankton C, N, mass	Displacement volume	Size-fract C, N, DW	Size-fract C, N, DW
Biology - Population & Community Measurements			
Chlorophyll *a*	Fluorometer (CTD profiles, discrete)	Yes	Yes
Taxon-specific phyto-pigments	HPLC (Goericke) Yes		Yes
Heterotrophic bacteria	Flow cytometry (Landry) Yes		Yes
Pico-phytoplankton	Flow cytometry (Landry) HOT	only	Yes
Nano- and microplankton	Epifluor-microscopy (Landry) HOT	only	Yes
Mesozooplankton, sentinel species	Microscopy (Ohman) No		Yes
Mesozooplankton, size composition	ZooScan (Ohman) No		Yes
Mesozooplankton, size distribution	Laser OPC (Checkley) No		Yes
Fish egg distributions	Nets and underway pumping	No	No
Ichthyoplankton Micr	oscopy	No	No
Krill & small pelagic fish	Bioacoustics, trawls (SWFSC, Koslow) No		No
Seabird abundance, distribution	Visual survey (Sydeman) No		No
Marine mammal census	Visual & acoustic survey (Hildebrand)	No	No

Fig. 2-20. Summary of methods used by CCE programs on CCE-augmented CalCOFI cruises. Methods used exclusively on the CCE Process Cruises are referred to in the proposal text.

Variable	Method	Reference
CalCOFI Measurements (for detailed information: www.calcofi.org and www.swfsc.noaa.gov)		
Hydrographic properties, continuous	Seabird 911 plus sensors & 24 place 10L rosette	www.seabird.com
Salinity, bottle	Guildline model 8410 Portasal conductivity	UNESCO 1981
Dissolved oxygen, discrete	Automated modified-Winkler titration	Culberson 1991
Nitrate, nitrite, phosphate, silicic acid	Autoanalyzer operated by SIO-ODF	Gordon et al. 1993
Chlorophyll *a*	Fluormetric analysis of acetone extracts	Strickland & Parsons 1972
Primary production	Noon to dusk on-deck ^{14}C uptake experiments	Steeman-Nielsen 1952
Mesozooplankton volume	Displacement volume of bongo tow sample	McGowan & Brown 1966; Ohman & Smith 1995
Fish egg distributions	Nets and underway pumping	Kramer et al. 1972; Checkley et. al. 2000
Ichthyoplankton (~400 species)	Microscopic analysis of bongo tow samples	Watson et al. 1988
CCE Measurements (for detailed information: www.cce.lternet.edu/data/methods)		
Nitrate, continuous	ISUS sensor, CTD-mounted	Johnson and Coletti 2002
Ammonium	Autoanalyzer operated by SIO-ODF	Gordon et al. 1993
Dissolved organic C & Total N	High temp oxidation (Shimadzu TOC-V)	Aluwihare et al. 2002
Particulate organic C, N	High temp combustion (Perkin Elmer 2400 EA)	Sharp 1974
Primary production (DOC)	^{14}C uptake – deck – activity in GF/F filtered SW	Mague et al. 1980
Taxon-specific phyto-pigments	Acetone extraction & HPLC analysis	Goericke & Repeta 1993
Heterotrophic bacteria	Stained samples on Altra flow cytometer	Monger & Landry 1993
Pico-phytoplankton	Stained samples on Altra flow cytometer	Monger & Landry 1993
Nano- and microplankton	Automated epifluoresence microscopy-image analysis	Taylor et. al. in prep.
Mesozooplankton, sentinel species	Microscope analysis of bongo-tow samples	Lavaniegos & Ohman 2007
Mesozooplankton, size composition	ZooScan analysis of vertical net samples	Gorsky et al. 2010
Mesozooplankton, size distribution	Laser OPC mounted in a bongo frame (0 to 210 m)	Herman et al. 2005
Krill & small pelagic fish	Multi-frequency acoustic survey (EK-60)	Demer et al. 1999
Mesopelagic fish	Oozeki fish trawl	Oozeki et al. 2004
Seabird abundance, distribution	Dawn to dusk visual survey	Tasker et al. 1984
Marine mammal census	Visual observers, acoustic buoys, towed hydrophone	Soldevilla et al. 2008

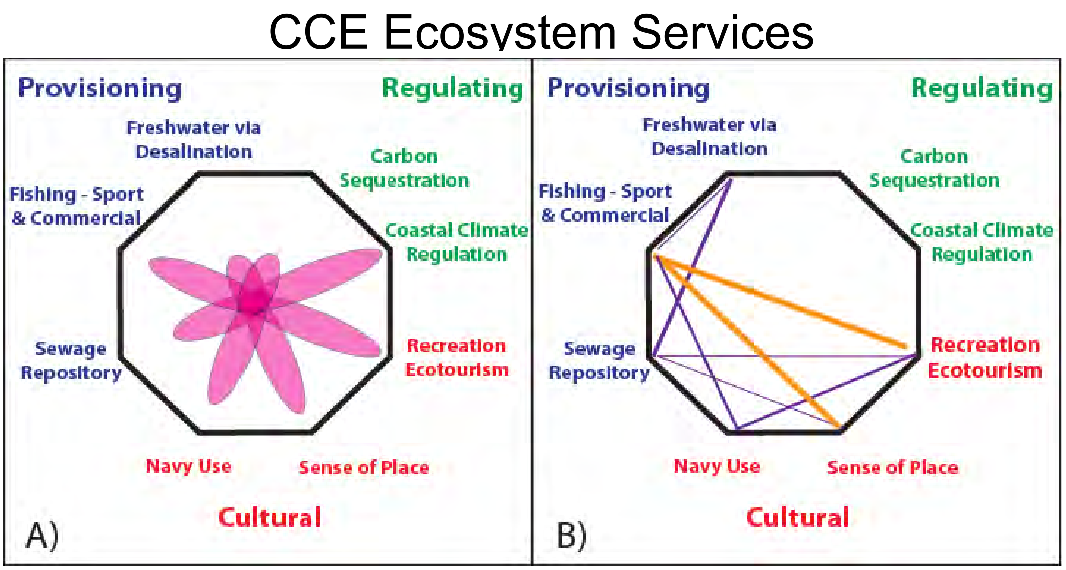

Fig. 2-21. CCE Ecosystem services: **A**) Petal diagram; the length of the petal depicts the relative importance of the ecosystem service. **B**) Interactions among services (violet – negative; ocher – positive). Classification of ecosystem services follows the Millennium Assessment (2005); all valuations are subjective. (Adapted from NTL-LTER Figure).

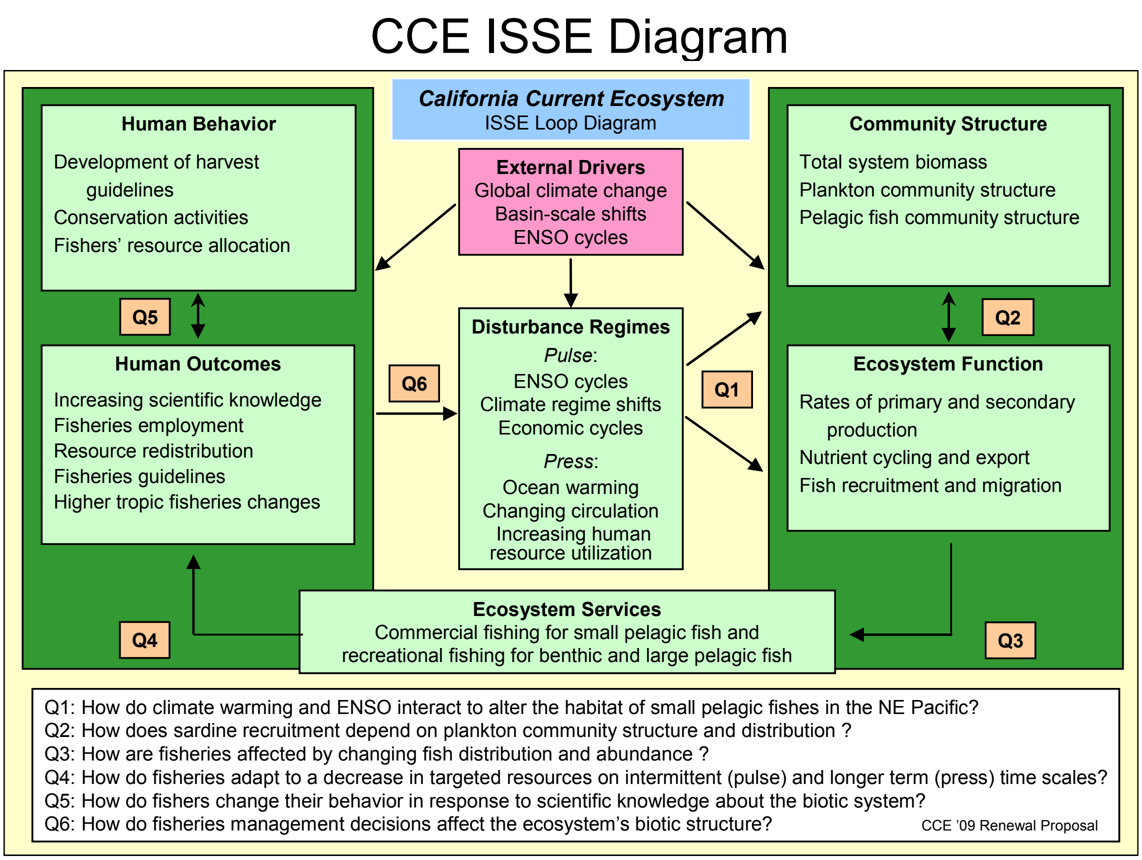

Fig. 2-22. ISSE feedback loop for CCE fisheries: Historically sardines and anchovies have been important off S. California. Today species targeted have broadened to include species of both commercial (sardines, rockfish, squid and tuna) and recreational (rockfish, seabass, tuna and swordfish) interest.

Fisheries Bioeconomic Model

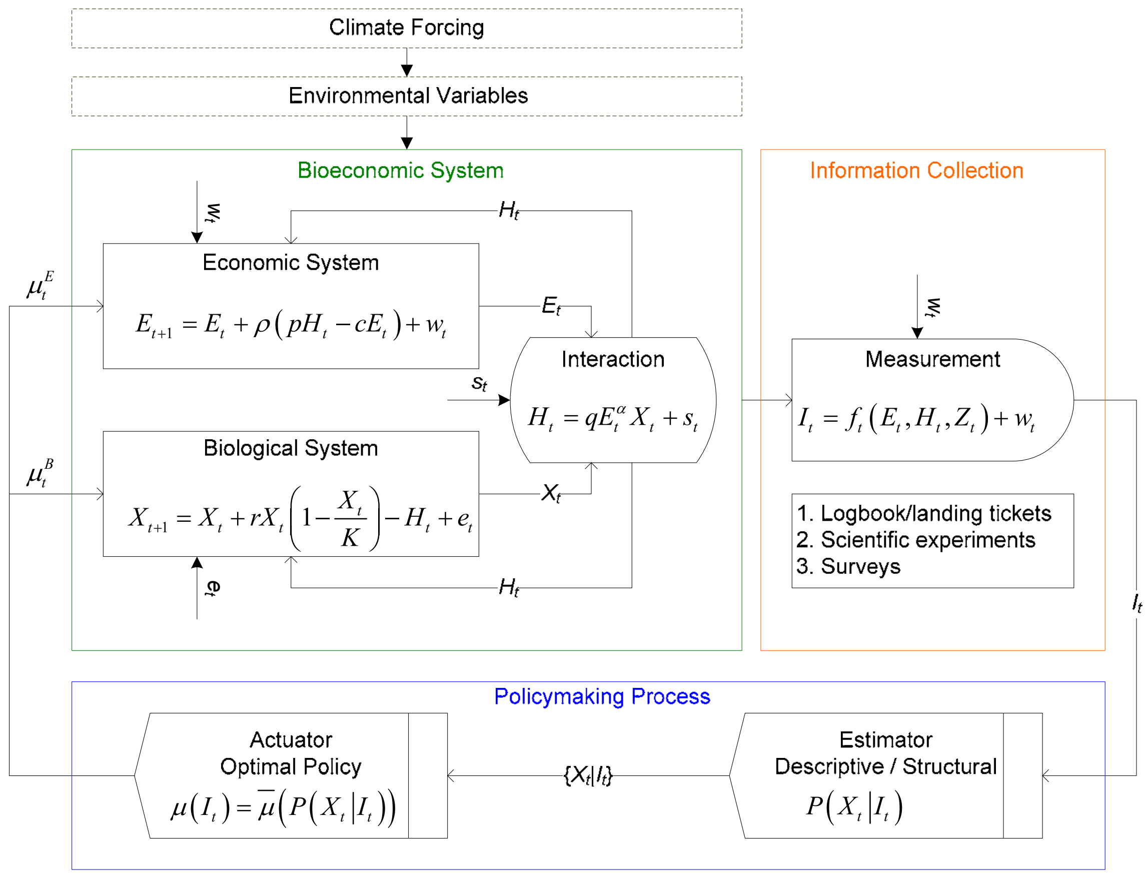

Fig. 2-23. This fisheries bioeconomic model includes interactions between the climate system, bioeconomic system, information processes, and policymaking processes. Two subsystems comprise the bioeconomic system: 1) the economic subsystem explains the dynamics of fishing effort *E*, and 2) the biological subsystem models the evolution of fish population *X*. These two subsystems are related by the fishery production process (*H*: harvest). The bioeconomic system is affected by environmental variables such as temperature, salinity, and currents, all of which are subject to climate forcing. Information processes are instrumental in measuring the system and delivering data for policy making. If some state variables such as fish stock are not directly observable, the policy making processes can be modeled by adaptive control with incomplete state information. It is implemented in two parts: 1) the estimator uses observed information such as catch and effort to infer stock as a conditional distribution ($\{X_t|I_t\}$), and 2) the actuator uses the inferred stock to generate the optimal economic policy μ_t^E and the optimal biological policy μ_t^B to the bioeconomic system.

Section 3. ***Site Management***

Participation in the CCE site, and site management

The CCE-LTER site is based at the Scripps Institution of Oceanography, University of California, San Diego (SIO/UCSD). Six additional institutions are represented as active participants (see Table 3-1). Currently, 28 scientists are involved in the site as either co-PI's or Associates, 21 of whom are located at SIO (Table 3-1; *N.B.* internally we define co-PI differently than NSF, which limits co-PI status to 5 individuals). A co-PI, by our definition, is someone for whom the CCE-LTER site is a major part of their research program, and some have overall project management responsibilities. Associates are engaged in the CCE site, but CCE represents a smaller part of their total research involvement. In addition to co-PI's and Associates, we have a category of "Affiliated Personnel" that includes visiting scientists, graduate students, and others who typically participate in one aspect of the research (e.g., on a single research cruise, or for a short-term collaboration). Participation in the CCE site by graduate students (44), postdocs (13), undergraduates (19), technicians (21), and volunteers (49) is recorded in Table 3-2. We have an open door policy toward collaborations and welcome involvement by other colleagues.

The site is managed by the Lead PI (M. Ohman), in regular consultation with the CCE Executive Committee (EXCO). The EXCO membership currently includes Mark Ohman, Karen Baker, Kathy Barbeau, Peter Franks, Ralf Goericke, Mike Landry, and Art Miller. These people represent each of the major elements of the CCE site (Process Cruises, Augmented CalCOFI and other time series, Modeling, Information Management, ISSE, Education, Outreach, and Capacity Building (EOCB)) and different science specialties. The EXCO addresses science and budgetary priorities for the CCE site, periodically reviews progress on each of the major program elements, responds to new science initiatives, prioritizes supplement requests, and serves as a communication conduit for the rest of the site. The EXCO also discusses major writing projects, including our current plans to write a review article based on the results of the first phase results from CCE and our eventual intent to produce a synthetic volume for the Oxford series on LTER sites.

CCE employs a half-time Program Office Coordinator (Robin Westlake Storey). She coordinates meetings, communicates regularly with participants in the CCE site and with the LTER Network Office, manages travel funds, assists with REU program management, maintains the site bibliography, and assists in assembling materials for annual reports and other documents.

CCE's Information Manager is Karen Baker, who is also a member of the EXCO. IM is closely integrated into CCE site science, EOCB, and planning.

The CCE Education, Outreach, and Capacity Building Coordinator is Beth Simmons, who is a certified teacher. She is physically located off site, but is in regular communication with the site PI, IM group, Program Office Coordinator, and with individual scientists or graduate students with whom she is working. She also coordinates our RET (Research Experience for Teachers) program.

A graduate student representative (currently Alison Pasulka) represents the interests of CCE graduate students and postdocs internally within the CCE site and to the LTER network. She coordinates the annual CCE graduate/student postdoc meeting, communicates student interests and concerns, and fosters interactions with grad students at other sites, to date especially at SBC and MCR.

Our REU program is coordinated by faculty member Kathy Barbeau, with assistance from Lihini Aluwihare and Mike Landry.

International collaborators. We encourage participation by colleagues abroad with common interests, and to date have developed successful collaborations with colleagues in Japan, France, Norway, Mexico, and elsewhere.

Communication within CCE

Internal communication within the CCE site membership is accomplished in several ways. (1) CCE holds an **annual meeting**, to which all participants in the site are invited. Off-site participants are encouraged to attend and travel support is provided. This meeting usually lasts 1½ days and includes summaries of all program elements, updates, new horizons, and discussions of any revised priorities. (2) The **CCE Forum** is our informal seminar setting for presentations and discussions. A Forum is held as needed, to focus on a particular PI 's or graduate student's results, to share preliminary interpretations (e.g., from our pilot front study), or other topical themes. (3) The lead PI distributes "**CCE-LTER News**" by email, to ensure that all participants (and especially those located off-site) are up to date on current events and planning. (4) Other, less formal **e-mail** communications are used to relay news from the LTER network office, NSF, or other sources. (5) **Video-conferencing** is now used, typically in combination with previously scheduled meetings. (6) Participants in the **Process Cruises** (usually 31-33 people at sea) have an excellent opportunity to interact informally at sea for approximately a month at a time.

Science and Budgetary Organization

The CCE site is organized around 6 core elements: **Process Cruises**, **Time Series Measurements**, **Modeling**, **Information Management**, **Integrated Science for Society and the Environment**, and **Education, Outreach, and Capacity Building.** There are separate budgets for each of these elements and for project management. An individual co-PI is responsible for managing each budget. The lead PI has electronic access to all budgets and maintains overall oversight. When a new year's budgetary allocation arrives from NSF, these funds are distributed in the manner described in the budget pages in the original proposal. If an adjustment is needed to the original plan, or a new opportunity arises, the issue is discussed by the EXCO, and funds may be reallocated.

The funds within CCE are distributed according to our agreed-upon needs for each program element, rather than proportionately to individual PI's. Most of the support goes to graduate students, technical support, permanent equipment, materials and supplies, and sample analysis. Relatively little support goes to PI salaries, all of whom seek additional funds elsewhere to complement the CCE-LTER funding. Travel funds are managed by the CCE project office. Discussions of needs for supplemental funds are conducted openly with the entire CCE group, and then the EXCO arrives at a prioritization of the supplement requests.

Table 3-1. **CCE-LTER Participants**

Name	Role	Institution	Interests
Mark Ohman	Lead PI	SIO	Mesozooplankton Ecology
Lihini Aluwihare	Co-PI	SIO	Dissolved Organic Matter
Karen Baker	Co-PI	SIO	Information Management
Katherine Barbeau	Co-PI	SIO	Iron Geochemistry
David Checkley	Co-PI	SIO	Mesozooplankton & Ichthyoplankton
Peter Franks	Co-PI	SIO	Biophysical Modeling
Ralf Goericke	Co-PI	SIO	Phytoplankton Ecology
Michael Landry	Co-PI	SIO	Food-Web Structure & Function
Art Miller	Co-PI	SIO	Physical Oceanography; Modeling
Greg Mitchell	Co-PI	SIO	Remote Sensing and Bio-optics
Farooq Azam	Associate	SIO	Bacteria/Microbial Food Webs
Steven Bograd	Associate	PFEL	Physical Oceanography
Ron Burton	Associate	SIO	Molecular Probes for Protists
Alexander Chekalyuk	Associate	LDEO	ALF systems / Phytoplankton
Russ Davis	Associate	SIO	Glider-based observations
Emanuel DiLorenzo	Associate	Georgia T.	Biophysical Modeling
Chris Edwards	Associate	UCSC	Ecosystem Modeling
Mati Kahru	Associate	SIO	Satellite Remote Sensing
Tony Koslow	Associate	SIO	Small Pelagic Fishes
Jennifer MacKinnon	Associate	SIO	Ocean Mixing
Todd Martz	Associate	SIO	Marine Chemistry
Brian Palenik	Associate	SIO	Microbial Diversity
Robert Pinkel	Associate	SIO	Iso- & Diapycnal Mixing Processes
Dan Rudnick	Associate	SIO	Mesoscale Ocean Physics
Beth Simmons	Associate	SIO	Education & Outreach
Ken Smith	Associate	MBARI	Deep-sea Benthic Ecology
Bill Sydeman	Associate	FIAER	Seabird Ecology
Junjie Zhang	Associate	UCSD	Environmental & Resource Economics

SIO= Scripps Institution of Oceanography/UCSD; PFEL= Pacific Fisheries Environmental Laboratory; LDEO= Lamont Doherty Earth Observatory; Georgia T.- Georgia Institute of Technology; UCSC= Univ. of California, Santa Cruz; MBARI=Monterey Bay Aquarium Research Institute; FIAER= Farallon Institute for Advanced Ecosystem Research; UCSD= Univ. of California, San Diego.

Table 3-2. **Numbers of student, postdoc, technical, and volunteer participants in CCE-LTER Phase I.**

Category	Graduate Students	Postdocs	Undergrad-REU	Undergrad-Other	Technical staff	Cruise Volunteers
SIO/UCSD	38	9	10	4	17	43
Other Institutions	6	4	3	2	4	6
TOTAL:	**44**	**13**	**13**	**6**	**21**	**49**

Section 4. ***Information Management***

CCE-LTER Information management (IM) has created an information environment that facilitates ecosystem research by establishing a digital data commons, augmenting existing data management efforts, and creating support for new data practices. Elements of the CCE-LTER information environment, grouped in framework, data, and infrastructure categories, are shown with their respective web links in Table 4-1. Included is a link to the CCE-LTER data policy that addresses data submission, availability, use, and acknowledgement, in compliance with the LTER Network Policy.

4.1 Introduction

In collaboration with site researchers, CCE IM has established the type of information environment required for a new site to become a fully functioning member of the LTER Network, a network known for its focus on time-series data and site-based IM. IM accomplishments include three framework elements and the establishment of infrastructure to support them. The framework elements are a) a CCE web site with database-backed dynamic information delivery that includes personnel, bibliography, media gallery, and event modules, b) a local information system that enables data viewing, query, plotting, and download as part of a multi-dimensional information architecture, and c) a data repository providing both research community and public access to datasets.

CCE-LTER has developed an informatics approach that takes into account technical, organizational, and social dimensions critical to development of a sustainable information environment. We have three specific information management aims:

> **Objective 1:** To provide data management services needed to capture, preserve, and provide access to data, as well as development of procedures for data presentation, quality control, and delivery.
>
> **Objective 2:** To design, develop, and enact an information management strategy that supports evolution of an information architecture as a framework for data organization and information systems development.
>
> **Objective 3:** To implement essential elements of data stewardship that enable the immediate local use of data and applications as well as facilitating long-term re-use of data.

The information environment resulting from this approach supports local data practices, data integration, and data interoperability. IM presentations and surveys at CCE meetings ensure regular communication with researchers. Tables summarizing states of completion of different datasets provide a management tool and a reminder about data submission requirements. Dialog continues at the IM design table where individual participants work directly with the IM team on tasks of interest. Features such as a new type of query, plot, or output format are added in response to specific requests from participants. Lags in data submissions are discussed periodically at CCE executive meetings as to whether additional attention is needed or additional support is required.

Several organizational arrangements ensure that information management is central to CCE site work: a) including the information manager as a member of the CCE executive committee, b) establishing a separate information management budget managed directly by the information manager, c) supporting information management at approximately 11-12% of the site basic budget, augmented by supplement opportunities, and d) working with science studies to investigate issues relating to data aggregation, data practices, and infrastructure building.

4.2 Information Environment Elements

As a new site, the CCE-LTER website has undergone continuing re-design, as content categories mature and new elements are added (e.g., dataset category listings, media gallery, at-sea blog, and prepared data views). The website has a three tier modular template structure and dynamic delivery of materials using relational database technology. Information about participants is delivered through PeopleZoo, a personnel directory that generates participant lists for the web site from a database that also produces the participant lists for ship cruises in the DataZoo information system. The bibliography module includes both a search interface for the general user as well as a web management interface for citation entry over the web. CCE Publication output available online is shown in Appendix 1. The media gallery is a third active interface making available on the web collections of photographs and videos along with their metadata. Data delivery on the web includes text and Excel download options while metadata are output in EML and local formats. In addition to web interface options, data exchange is being developed via web services for machine-to-machine or repository-to-repository communication.

The CCE-LTER information architecture has a multi-project, open source framework. Since 2005 the DataZoo information system has grown from a one-component system to a service-oriented, three-component system with a suite of supporting resources (Table 4-2). DataZoo is a queriable information system redesigned to accommodate multiple projects based upon robust data and metadata models. The well-developed local metadata are delivered according to different needs, including EML specification for the ecological community and NetCDF for ocean observing communities. Interdependent sets of controlled vocabularies including keywords, code, unit, attribute, and qualifier dictionaries have been developed as part of the site metadata system describing datasets to the column level. The information system supports both user and management interfaces while providing updated data access, visualization, and basic data integration. In addition, a suite of tools is growing including a grid converter and a dynamic mapper. It is a relational system with an object-oriented program layer.

LTER CCE datasets are summarized in Appendix 2, some extending over decades of time because of the CalCOFI program which preceded the formation of CCE. The NSF 2-year policy is observed for time-series datasets which are updated annually. Selected datasets may be targeted for more rapid availability when individual interests or group synthesis activities have been identified. Early versions of many datasets are posted shortly after a process cruise on individual cruise data pages prior to their full processing and publication into DataZoo. Procedures exist to make datasets available quickly online in order to enable discussion. In this case, access may be restricted to the local community temporarily until issues such as quality control concerns are resolved. To date all datasets submitted have been intended for public access. Since our site review, metadata have been completed and datasets submitted to Metacat. A summary of CCE-LTER data use is provided in Table 4-3 and repeated in Appendix 2.

Computational infrastructure is provided through participation in the Computation Infrastructure Services (CIS) facility associated with the Integrative Oceanography Division at SIO. Development of a recharge facility in 2007 stabilized the CCE-LTER technical infrastructure, providing hardware and software services including an expanding electronic hub of collaboration software, storage and backup, authentication and security, as well as ready access to expertise on new technologies and techniques. In addition, an IM-developed eventlogger has been developed and adopted as part of the oceanographic fieldwork infrastructure, thereby facilitating flow of data from field to database (see Photo 1). Use of the eventlogger software for a graduate student-led cruise indicates changing collaborative data practices.

Ocean Informatics has been developed as a conceptual framework to support the requirements associated with a local information environment for research involving heterogeneous data (Baker et al. 2005; Baker and Chandler 2008). CCE IM works in close collaboration with Palmer Station LTER, CalCOFI at Scripps, and NOAA Southwest Fisheries Science Center. Working with other long-term oceanographic projects creates a critical mass and a momentum through pooling of resources and expertise that benefits all participants. Personnel associated with the informatics infrastructure have expanded during the CCE first cycle from a single individual to an informatics team with close connections to a separate computational infrastructure team. This collaboration makes available the breadth and depth of diverse skills required for a local LTER site to design systems and steward a dynamic data repository (Photo 2). Basic work entails data management, organization, and delivery while advanced skills are required for database design, systems architecture, data modeling, and semantic structuring. IM is also a research activity that contributes to an emergent understanding of site-based information management and developing issues associated with data and growth of sustainable infrastructure (Bowker et al. in press).

4.3 Collaborative Endeavors: LTER Network & Other Collaborations

The CCE IM team is engaged within the LTER Network via leadership of the LTER IM Dictionary Working Group (WG) and Governance WG, through editorship of IM Databits Newsletter, and as a new member of the Network Information System Advisory Committee (NISAC). As lead on the Unit WG, a post ASM proposal outlined the development of a unit registry being designed to support an all-site unit dictionary. These activities are planned to stimulate and inform CCE informatics capacity-building and local inquiry-based learning. In collaboration with the Ohman Lab and SIO Collections, a Zooplankton Dataspace was created to bring together several zooplankton databases and their interfaces; with CalCOFI and NOAA Southwest Fisheries, a public interface for ichthyoplankton data was designed. The development of specialized interfaces for these datasets (Table 4-1) that extend back more than sixty years enables publication of subsets of the highly complex data as highly-structured, time-series datasets into DataZoo and Ecotrends. In concert with EcoTrends data work, a dataset identification scheme was developed to provide an accession number for existing datasets. With a number of national oceanographic data efforts in development, CCE is working with the NOAA Pacific Coast Ocean Observing System (PACOOS) community and is exploring interfaces with ocean observing systems. In collaboration with the Ocean Institute, a CCE EOCB participant, a set of web-based data entry and management applications has been created to support chlorophyll-temperature data collection, quality control, and publication into the CCE information system for both educational and research purposes.

Affiliation with the UCSD Science Studies Program and collaboration with national and international colleagues contribute to our conceptual infrastructure. We have published on topics relating to the work of IM in theory and in practice: standards (Millerand and Bowker 2009), data practices and information systems (Karasti et al. 2007; Millerand and Baker 2009), infrastructure-building (Baker and Millerand 2007a,b; Karasti and Baker 2008a,b), interoperability (Ribes et al. 2005), repository federation (Baker and Yarmey 2009), information ecologies (Baker and Bowker 2007) and the role of information management (Baker et al. 2000; Karasti and Baker 2004; 2008; Karasti et al. 2004; Baker and Millerand in press).

4.4 Future Directions

Future directions include building out our infrastructures and developing an abstraction layer. An abstraction layer is a generalized interface that hides implementation details of highly complex and very large data collections (Table 4-3). We also plan to improve the DataZoo metadata model as well as methods for capturing data. DataZoo usability has been assessed to date through individual design sessions in the Design Studio central to the CCE information environment (see Photo 3). We plan to add a new approach in the next cycle by using a panel to review and assess the information system. New features have been identified for implementation in the next years: expansion of existing applications such as DataZoo report generation and visualization, development of a production level geographic dictionary (a gazetteer) and a methods library, augmentation of the attribute system and the data integration interface, and development of an abstraction layer over the multiple components of the CCE-LTER information system. The IM trajectory includes continuing to balance growth of personnel, infrastructure, and framework elements together with a focus on design and learning as central tenets of the CCE site-based information management strategy.

Table 4.1 Overview of CCE LTER Information Environment Elements		
element type	element	link
Framework	Web site	http://cce.lternet.edu
	DataZoo information system	http://oceaninformatics.ucsd.edu/datazoo
	Data repository	http://oceaninformatics.ucsd.edu/datazoo/resources/documentation?action=view&page=Design_and_Architecture
Data	Dataset catalog	http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/datasets
	Initial process cruise data pages	http://cce.lternet.edu/data/cruises/
	Zooplankton dataspace	http://oceaninformatics.ucsd.edu/zooplankton
	Ichthyoplankton data interface	http://oceaninformatics.ucsd.edu/ichthyoplankton/
	Ocean Institute data collection	http://oceaninformatics.ucsd.edu/oceaninstitute
	Glider data	http://spray.ucsd.edu
	Remote sensing data	http://spg.ucsd.edu/Satellite_Projects/CCE-LTER/Satellite_support_for_CCE-LTER.htm
Infrastructure	Computational infrastructure	http://iod.ucsd.edu/compu/computation.html
	Informatics infrastructure	http://oceaninformatics.ucsd.edu
	Conceptual infrastructure	http://interoperability.ucsd.edu
	Data policy	http://cce.lternet.edu/data/policy.php

Photo 1: Eventlogger designed for mobility shown as close-up and in use on the bridge of a ship.

Photo 2: The CCE LTER informatics team: a reading group activity and an extended infrastructure team assembly.

Table 4.2 Infrastructure and Information System Databases			
Data Types	Database	Interface	Output Type
Infrastructure	Personnel	Search	HTML
	Bibliography	ResourceList	HTML
	Studies	Search/webservice	XML
	Platforms	search/webservice	XML
	Unit Registry	webservice	XML/JSON
	Attribute Dictionary	Dictionary	HTML
	Code Dictionary	Dictionary	HTML
	Cruise Registry	Registry	
	Station Registry	Registry	
Highly Structured	Datazoo	Datazoo	Query & Download
			View & Plot
			EML Metadata
			NefCDF generic
			NetCDF OceanSites
Very Complex	ZooDB	Zooplankton Dataspace	Query & Download
			View & Plot
	IchthyoDB	Ichthyoplankton	Query & Download
			Sampling Plot
			Metadata
		webservice	XML
Very Large Homogeneous	CTD	FileFinder	Query & Download

Table 4.3 CCE LTER Data Downloads				
Use Category	Visit	Plot	Download	Total
Academic Research	891	205	244	1340
IOD Local Use	632	210	125	967
Government Agency	39	40	8	87
Education (K12)	37	14	5	56
Non-Profit Agency	14	1	0	15
Private Industry	5	0	0	5
Other	6	7	3	16
Not Supplied	2	2	1	5
Total	1846	580	426	2851
% of total	65%	20%	15%	100%

Summary of logging of access for 2007-2009 to the LTER CCE datasets available online via the information system Datazoo. The summary excludes access by members of the Ocean Informatics team.

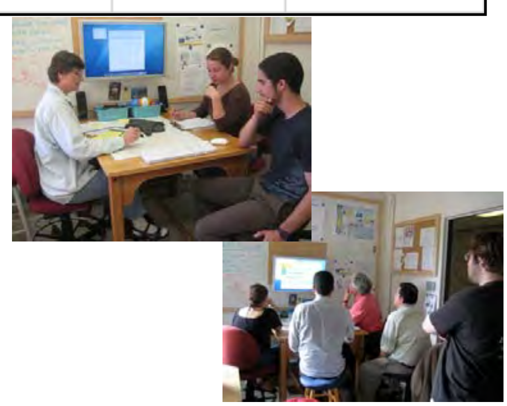

Photo 3: Discussions in the design studio where CCE participants engage as co-designers.

Section 5. ***Education, Outreach, and Capacity Building***
Program Description and Historical Reference http://cce.lternet.edu/outreach/

Education, Outreach, and Capacity Building (EOCB) for the California Current Ecosystem LTER program (CCE-LTER) provides inquiry science education, training, and outreach in a variety of settings. From 2004 – 2005, a part-time EOCB coordinator (Beth Simmons) focused program efforts on infrastructure organization. She established collaborations with informal marine science facilities including the Birch Aquarium at Scripps, the Ocean Literacy Network, the Ocean Institute in Dana Point, the National Marine Educators Association (NMEA), and the National Science Teachers Association (NSTA). Since 2005, we built and extended our EOCB program efforts formally through classroom visits and professional development opportunities, making use of local classrooms at Rancho Bernardo High School, the University of California at San Diego (UCSD) Preuss School (a low income-serving school), and Rancho Santa Fe Middle School. Between 2006 and 2008 we strengthened local ties through our participation in such events as pier walks, additional school visits and several UCSD-sponsored Open Houses. Our EOCB program engaged in both the *process* and the *understanding* of site science through the organization of Picture of the Day on two CCE-LTER scientific process cruises and by sending two credentialed teachers to sea. Within the Schoolyard LTER community we contributed a chapter for the SLTER Education Handbook and coordinated an SLTER site assessment survey.

We built an RET program, involving four teachers from three different local schools with the goal of advancing opportunities for local marine science educators seeking to gain professional teaching and research experience. These experiences enabled teachers to participate in site research projects on topics like the sensitivity of krill to changes in the physical environment and to develop lesson plans surrounding our Chlorophyll-Temperature Time Series project with the Ocean Institute, which has directly involved over 1200 students in an ocean measurement program. Our cross–site children's book entitled *Sea Secrets: Tiny Clues to a Big Mystery* was released in September 2008. This book project has created an opportunity to begin broad-based outreach. Facilities like the Birch Aquarium have helped us organize events centered on the children's book, exposing CCE site science and research methods to over 1600 participants and local San Diego residents, children, and parents. Numerous book signing events and classroom visits have helped us sell over 500 books and donate over 300 books to various schools and other outreach venues. The book has presented us an opportunity to share science through a product that is a vehicle to learn science, a resource to develop ocean literacy, and a tool with which to teach.

CCE science has contributed to the education of students at several levels. CCE graduate students have taught a summer course for high school students in 4 successive summers; 3 CCE graduate students currently have GK-12 fellowships and are working in high school science classrooms; and CCE site science has been incorporated into 3 undergraduate and 5 graduate courses. Thirteen REU students have participated in summer research projects, and several have applied to or matriculated in graduate school.

CCE-LTER EOCB draws upon the remarkable group of research scientists, graduate students, information managers, programmers, educators, students, and volunteers to sustain the outreach program since its inception in 2004 and educate others on California Current Ecosystem science.

Category	Grad. students	Postdocs	Undergrad-REU	Undergrad-Other	Technical staff	Cruise Volunteers	High School summer courses	Undergrad Courses	Grad Courses
SIO/UCSD	38	9	10	4	17	43	4	2	5
Other Institutions	6	4	3	2	4	6	0	1	0
TOTAL:	**44**	**13**	**13**	**6**	**21**	**49**	**4**	**3**	**5**

Table 5-1. Involvement of graduate students, postdocs, undergraduates, technical staff, and cruise volunteers in the CCE site. The last 3 columns report courses offered at the high school (summer session), undergraduate, and graduate levels that draw on CCE data and results.

Broadening of K – 12 Educational Activities and Public Awareness

Drawing upon our historical successes, the coming six years will reflect the growth and innovation of the CCE-LTER EOCB program as we broaden our vision, build new learning opportunities utilizing our educators, and strengthen our collaborations. We seek to articulate the importance of CCE dynamics, to generate greater public awareness of California coastal ecosystem science, and to expand and diversify human resource capacity in marine ecology.

Our efforts will include strengthening existing collaborations with Ocean Institute (OI), the Ocean Literacy Network, NMEA, and the NSTA. This will be accomplished by supporting the needs of the floating laboratory classes at OI by modifying our current instructional materials to meet the needs of the classes offered by OI, aligned with the essential principles of Ocean Literacy. Our participation in the NMEA annual marine educators conferences will continue to serve as an assessment tool for our outreach program, providing feedback regarding the utility of our materials, and the potential for building new collaborations. As our educational materials are revised, the NSTA Science Teacher magazine will serve as a platform for submitting articles for publication, bringing CCE science to a larger audience of educators and validating our outreach efforts in a greater professional science education community. A new collaboration with the NOAA Ocean Today program, a part of the Sant Ocean Hall of the Smithsonian Institution's National Museum of Natural History, will allow CCE EOCB to formulate educational stories surrounding key themes. These will include how long-term ocean warming affects ocean food webs, how changes in the stratification of the California Current influence physical and biological balances within the ecosystem, the consequences of ocean acidification, and the ecological effects of fronts and eddies in coastal upwelling ecosystems. These stories will be created and designed to inform and educate the public, be highly visual, and also have an interactive element. Once submitted to NOAA's Ocean Today kiosk program they can be viewed at up to 22 museums and aquariums around the United States and Mexico. The EOCB coordinator will work closely with independent web development media specialists and build collaborations with other education curriculum writers from this network, all of whom excel in creating professional, interactive educational multimedia experiences.

An additional platform to launch new learning opportunities exists within our CCE Research Experience for Teachers (RET) program. This program has served as a professional development opportunity for K – 12 educators in underrepresented schools and afforded several Teacher-at-Sea experiences to local educators in diverse socioeconomic areas. Building from this success, we will enlist the experience and enthusiasm of our CCE graduate students. Our goal is to help cultivate dynamic learning experiences for both educators and students, in order to bridge CCE research with classroom pedagogy. Over the course of six years these collaborative experiences will produce coordinated outreach materials that focus either on a grad/undergraduate's research, an 'at sea' experience, or existing needs within a classroom curriculum. Our targeted audience will begin with students from educator participants at the Patrick Henry High School and then reach out to the greater San Diego Unified School district, specifically targeting local low-income and minority students. The outreach coordinator will bring together the needs of all participants and co-create products utilizing our website to display these resources and draw in the general public.

We plan to continue our active REU program, and use this as a vehicle to recruit under-represented students into the ocean sciences.

As co-chair of the Schoolyard Education Committee, the CCE EOCB Coordinator will continue to be actively involved with the LTER and Schoolyard network. With interest in the Children's Book Series Project, CCE EOCB will be at the forefront of the long-range vision of the program. This will allow us to assess CCE's next phase of involvement in the book series project. We will research the broad range of textual, visual and cultural challenges in translating a children's book, and seek to modify our instructional materials to make them more readily available to Spanish-speaking, ESL students within the greater San Diego community.

CCE Collaborators - Education, Outreach, and Capacity Building

Aquarium of the Pacific - Interactions with the aquarium in Long Beach, CA for education.
Aquatic Adventures - CCE provides opportunities for AA staff to volunteer at sea.
DLESE - Digital Library for Earth System Education.
Exploratorium - Collaborative educational work, located at the San Francisco Museum.
National Marine Educators Association - NMEA annual meetings for Education and Outreach participation.
NSDL - National Science Digital Library.
National Science Teachers Association (NSTA) – Online workshop.
Ocean Institute – Dana Point, CA – Chlorophyll and temperature time series as part of outreach curriculum.
Ocean Literacy Network - Ocean literacy on-line meeting place for educators and scientists.
The Preuss School, UC San Diego - Science curriculum development with teachers from UCSD's Preuss school.
Rancho Bernardo High School - Science curriculum development for high school students.
Rancho Santa Fe Middle School - Marine science educational visit from middle school students.
Santa Clara University - Relations with the Science, Technology and Society Institute.
UC San Diego-COSMOS -UC math & science summer school enrichment program, grades 8-12

CCE Education, Outreach, and Capacity Building

Fig. 5-1: From L to R - *Sea Secrets* illustrator Kirsten Carlson, CCE lead PI Mark Ohman, and co-author Beth Simmons in Estes Park at the 2009 All Scientists Meeting / SLTER Children's Book Signing event.

Fig. 5-2: *Teacher at Sea* participant Christy Millsap (L) from Rancho Bernardo high school, alongside other volunteers on the October 2008 CCE LTER Process cruise aboard the R/V *Melville*.

Fig. 5-3: CCE graduate student Moira Decima volunteers at the Birch Aquarium Family Days event. in February 2008 showcasing the science of our *Sea Secrets* children's book.

Fig. 5-4: Students aboard the R/V Sea Explorer participating in the Floating Lab classes with our collaborators at the Ocean Institute in Dana Point, CA.

Fig. 5-5: Professional growth opportunity for marine science educators on the Scripps Pier.

Fig. 5-6: E&O coordinator Beth Simmons working with middle school science classes on zooplankton ecology.

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Appendix 1 : CCE LTER Publications, 2005-2009 (140 total)

I. JOURNAL ARTICLES (108)

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Appendix 2. CCE-LTER Online Datasets and Usage

The datasets below are publically available from the CCE LTER website and from the DataZoo information system directly at **http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/datasets**. The dataset ID is unique, a key to finding the datasets online. The dataset type indicates whether the dataset originates on a CCE process cruise, a CalCOFI augmented survey cruise, or as a result of subsequent processing (product). In some cases, cruise samples have been taken and archived so are in the queue for analysis. The last columns lists the current contact or responsible investigator. The CalCOFI augmented cruises began in late 2004; the three CCE process cruises were in May 2006, April 2007, and October 2008.

Dataset ID	Collection Type	Dataset Title	Responsible Investigator
Physical Environment			
143	process	Underway Sea Water Intake and Meteorological Data - 1 Minute Averages	R. Goericke
10	process	Conductivity Temperature Depth Bottle Data	R. Goericke
82	survey	Conductivity Temperature Depth & Phytoplankton Chlorophyll Bottle Data	R. Goericke
7	process	Conductivity Temperature Depth Profiles	R. Goericke
53	process	Underway Sea Water Intake and Meteorological Data	R. Goericke
152	product	Secchi Disk Depth - Mean Annual	R. Goericke
63	process	Underway Ocean Currents (ADCP)	M. Ohman
175	product	Pacific Decadal Oscillation (PDO) Index	External
173	product	North Pacific Gyre Oscillation NPGO index monthly averages	M. Ohman
16	station	San Diego Sea Level - Monthly Averages	External
153	product	San Diego Sea Level and Anomalies - Monthly Averages	M. Ohman
13	station	San Diego Weather - Daily Averages	External
14	product	San Diego Weather - Monthly Averages	External
15	station	Scripps Institution Of Oceanography Pier Water Temperature	External
60	product	Photosynthetically Active Radiation - Daily Integrated	G. Mitchell
61	process	Photosynthetically Active Radiation	G. Mitchell
Biogeochemistry – Elemental Stocks & Rates			
20	process	Total Organic Carbon and Total Nitrogen	L. Aluwihare
22	process	Dissolved Inorganic Nutrients	R. Goericke
54	survey	Particulate Organic Carbon and Nitrogen	R. Goericke
104	process	Particulate Organic Carbon and Nitrogen	R. Goericke
62	process	Sediment Trap	M. Stukel
166	survey	Zooplankton Biomass (Displacement Volume) - Spring Annual Averages	M. Ohman
21	survey	Dissolved Iron	K. Barbeau
181	process	Dissolved Iron	K. Barbeau

Biology - Population & Community Measurements			
11	process	Chlorophyll	R. Goericke
72	process	High Performance Liquid Chromatography Pigments	R. Goericke
71	process	Primary Production - Particulate	R. Goericke
176	product	Integrated Primary Production	R. Goericke
113	survey	Size Fractionated Chlorophyll	R. Goericke
119	process	Size Fractionated Chlorophyll	R. Goericke
17	product	California Current Ecosystem Data Summary - Annual	R. Goericke
18	product	California Current Ecosystem Data Summary - Cruise Averages	R. Goericke
55	process	Picoplankton and Bacteria Abundance	M. Landry
76	process	Picoplankton and Bacteria Biomass	M. Landry
57	survey	Nano and Microplankton Biomass	M. Landry
58	survey	Nano and Microplankton Abundance	M. Landry
180	process	Nano and Microplankton Biomass	M. Landry
179	process	Nano and Microplankton Abundance	M. Landry
159	survey	Picoplankton and Bacteria Abundance	M. Landry
172	survey	Zooplankton Abundance of Cool Regime Salps Sentinel Species Group - Spring Annual Averages	M. Ohman
155	survey	Zooplankton Abundance of Euphausiid Sentinel Species - Spring Annual Averages	M. Ohman
171	survey	Zooplankton Biomass (Organic Carbon) of Pelagic Tunicates - Spring Annual Averages	M. Ohman
149	product	Zooplankton Biomass (Organic Carbon) - Spring Annual Averages	M. Ohman
170	product	Mesozooplankton Biomass (Carbon) - Spring Annual Averages	M. Ohman
167	survey	Ichthyoplankton Abundance and Zooplankton Displacement Volumes - Oblique Tows	E. Weber
168	survey	Ichthyoplankton Abundance - Vertical Tows	E. Weber
169	survey	Ichthyoplankton Abundance - Surface Tows	E. Weber
111	survey	Bird and Mammal Census Log - CalCOFI cruises	W. Sydeman
112	survey	Bird and Mammal Census - CalCOFI cruises	W. Sydeman
162	product	Bird Community Abundance and Richness - Seasonal	W. Sydeman
164	product	Bird Species Abundance - Seasonal	W. Sydeman
19	station	Ocean Institute Chlorophyll	R. Baker

Table 4.3 CCE LTER Data Downloads

Use Category	Visit	Plot	Downloac	Total
Academic Research	891	205	244	1340
IOD Local Use	632	210	125	967
Government Agency	39	40	8	87
Education (K12)	37	14	5	56
Non-Profit Agency	14	1	0	15
Private Industry	5	0	0	5
Other	6	7	3	16
Not Supplied	2	2	1	5
Total	1846	580	426	2851
% of total	65%	20%	15%	100%

Summary of logging of access for 2007-2009 to the LTER CCE datasets available online via the information system Datazoo. The summary excludes access by members of the Ocean Informatics team.