OVERVIEW OF CALIFORNIA CURRENT ECOSYSTEM

LONG-TERM ECOLOGICAL RESEARCH SITE (CCE-LTER)

RESEARCH ACTIVITY, INFORMATION MANAGEMENT, AND EDUCATION

AND OUTREACH

SITE REVIEW 17- 18 Sept. 2007

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TABLE OF CONTENTS

PREFACE

This document is not intended to be a comprehensive statement of CCE accomplishments or to address all aspects of CCE site activities. Instead it summarizes several elements of the CCE program.   We encourage the site review team to ask questions to expand upon or clarify any aspect of our research, information management, or education and public outreach activities. Cross-site interactions (with other LTER and non-LTER programs) will be discussed in La Jolla.

Please remember that many results presented herein are unpublished.

LTER: Nonlinear Transitions in the California Current Coastal Pelagic Ecosystem (CCE)

We propose to create an LTER site in the **coastal upwelling biome** of the California Current System. The research will focus on mechanisms leading to temporal transitions between different states of the pelagic ecosystem. Observations from the CalCOFI coastal ocean time series–currently in its 55th year–demonstrate the importance of external forcing of the pelagic ecosystem on multiple time scales, including: **El Niño**, the multidecadal **Pacific Decadal Oscillation**, and a multidecadal **secular warming trend**. Interactions of such forcing and biotic interactions can lead to nonlinear ecosystem responses that may be expressed as relatively abrupt transitions. We propose to evaluate four hypothesized mechanisms for such ecosystem transitions:

- *Sustained, anomalous alongshore advection of different assemblages*
- *In situ food web changes in response to altered stratification and nutrient supply*
- *Changes in cross-shore transport and loss/retention of organisms*
- *Altered predation pressure*

The California Current Ecosystem (**CCE**) LTER site will address these hypotheses with an integrated research program having three primary elements: (1) **Experimental Process Studies** will initially focus on the hypothesis of in situ food web changes. (2) **Time Series Studies** will evaluate alternative hypotheses using space-resolving time series measurements, including high frequency temporal measurements at different nearshore locations, satellite remote sensing, and an extensive quarterly measurement program at sea that will capitalize on and significantly enhance the CalCOFI time series. (3) **Modeling and synthesis studies** will help quantify the dynamics underlying the observations; provide a platform for hypothesis testing through numerical experiments and process models; provide a means for dynamic interpolation between observations in space and time; and help optimize the field program.

The proposed study region is an ideal location for an LTER site: it has 5 decades of climate context provided by CalCOFI; it is in a biogeographic boundary region, making it an early sentinel of climate change; it has pronounced spatial gradients in a relatively small geographic area; its anoxic basins provide a unique connection to paleoceanographic studies; and the extant 4-D physical ocean circulation model of the region will permit rapid advances in the development of coupled bio-physical models of ecosystem transitions. The site will allow the LTER network to compare *coastal pelagic upwelling ecosystems* with other biomes with respect to: **Pattern and control of primary production, Spatial and temporal distribution of populations selected to represent trophic structures, Patterns of inorganic inputs and movements of nutrients,** and **Patterns and frequency of disturbances.**

Broader Impacts: We will have state of the art **Information and Data Management**, to serve data and metadata internally, to other LTER partners, educators, the general public, and policy makers. An active **Education and Outreach** program will team scientists with CA COSEE and 3 external partners to engage the "K through grey" community in both the *process* of and the *understanding* gained from this research. We will train undergraduates, graduate students, and postdoctoral scholars across disciplinary boundaries. Through collaborations with informal science education organizations, we will reach hundreds of K-12 schoolchildren each year, including local low-income and minority students; teachers and students will participate in our field studies and gain training in oceanographic science. We will assist in the development of new school curricula and develop outreach materials illustrating the implications of coastal ocean variability for those who depend on resources of the coastal zone.

EXCHANGING TIME FOR SPACE: Process Studies

Consistent with our original LTER proposal, experimental process studies in the CCE have initially focused on one of the hypothesized mechanisms leading to climate-related ecosystem transitions -- **altered stratification and nutrient supply**. According to this hypothesis, changes in vertical stratification of the water column alter rates of nutrient supply and drive predictable and quantifiable changes in primary production and phytoplankton composition, which propagate to higher trophic levels via food-web pathways of energy flow. Ecological processes and interactions at the base of the food web have both practical and strategic rationale as our starting point: 1) results from our site document increased density stratification in the CCS over the past half century; 2) shipboard experimental techniques are well suited to the time scales of organisms, like phytoplankton, bacteria and protozoa, with rapid doubling times; 3) processes regulating primary production, nutrient cycling and organic fluxes are core cross-cutting elements of the LTER network, and they directly link community ecology and biogeochemical research interests in the CCE; 4) experimental and observational data on the microbial community, a major gap in long-term CalCOFI studies, are essential for parameterizing and validating CCE ecological models, which can be used, in turn, to test other hypothesized mechanisms for system transitions on decadal scales. To date, two of our three proposed process studies have been successfully completed on CCE cruises in May-June 2006 (P0605) and April 2007 (P0704). The third is planned for seasonally contrasting oceanographic conditions in late summer 2008.

Our study region is along the axis of CalCOFI line 80 off Point Conception, an area of sharp cross-shore gradients in water-column and community characteristics. As a key element of our experimental strategy, we explicitly exploit this spatial variability as a substitute for climate-driven temporal variability. This time-for-space exchange is accomplished by selecting study sites representing a range of initial conditions typical of different ecosystem conditions. Using a Lagrangian design, we then conduct several-day cycles of observational and experimental activities around each to elucidate their contrasting system dynamics and community trajectories. Water parcels are marked with a drogued, satellite-tracked drifter, which serves as moving frame of reference for shipboard sampling as well as an *in situ* incubation platform for experimental (manipulation) studies of primary production, phytoplankton growth and microzooplankton grazing. Routinely measured system variables include: temperature, salinity and density (CTD); currents (ADCP); bio-optical parameters (PAR, backscattering, spectral irradiance, absorption and attenuation, phytoplankton photosynthetic potential), nutrients (dissolved inorganic N, P, Si); dissolved and particulate iron (Fe); total and particulate organic carbon and nitrogen (C, N); stable isotopes of C and N; biogenic silica; thorium-uranium disequilibrium (particle export); fluorometric Chla and HPLC accessory pigments; microscopical, flow cytometric and molecular samples for assessing microbial community composition; abundance, biomass, size structure, and grazing rates of mesozooplankton; and recently, abundance and diets of migratory mesopelagic fishes. Shipboard experiments are conducted for primary production (P vs E), bacterial production, bacteria-particle interactions and enzyme activities, trace element (Fe, Co) limitation of production, and mesozooplankton grazing and reproduction.

Additional drift arrays were also used on the April 2007 cruise to directly measure differences between sites in the passive vertical export of sinking particulates into drifting sediment traps. The depth distributions and variability of zooplankton and organic aggregates are assessed with a profiling SOLOPC drifter that includes a CTD, fluorometer, and Laser Optical Particle Counter. In summary, our process cruises are designed to follow the temporal evolution of marked parcels of

water for 4-5 days while conducting experimental studies to assess the contributions of phytoplankton and bacterial growth, micro- and meso-zooplankton grazing and active vertical migrations to net community change, ecological interactions and biogeochemical fluxes.

Detailed Cruise Reports containing initial impressions and results from the completed cruises are available on the CCE website. In the summary below, we highlight a few of the emergent themes and early accomplishments of the process studies.

Spatial and Temporal Context

One of the major challenges in studying ecosystem dynamics in a fluid pelagic environment is the confounding of temporal and spatial scales of variability. Even, and perhaps especially, for Lagrangian-designed process studies, we need to know how our detailed experiment results in a moving patch of water are embedded in the broader context of system variability and change. One important early accomplishment of CCE is therefore the successful implementation and integration of new sampling technologies to provide the large-scale context for site selection, experimental interpretation and, ultimately, validation of 3-D coupled physical-ecological models.

Both leading up to and during cruises, the availability of processed satellite images of sea-surface temperature (SST) and Chla from Mati Kahru (**Fig. P1**) has greatly facilitated experimental site selection and understanding the direction of system changes on a broad horizontal canvas. At the same time, continuous *Spray* glider surveys have provided unprecedented insights of patterns and features in temperature, fluorescence and currents at depth. In addition to routine surveys, Russ Davis and Mark Ohman have effectively used a

Fig. P1. Drifter tracks superimposed on MODIS surface Chla for Process Cruise P0605.

Spray glider to follow the evolution of the 3-D biophysical structure in the vicinity of our experimental drift array. The section plots in **Figure P2** illustrate a series of vertical sections that alternate along and across the axis of drifter flow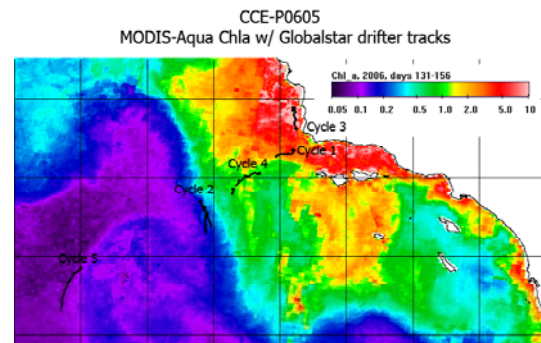 during CCE-P0605. Red vectors are average glider-resolved current velocities in the upper 150 m. The reproducible physical (T, S, density) and acoustic
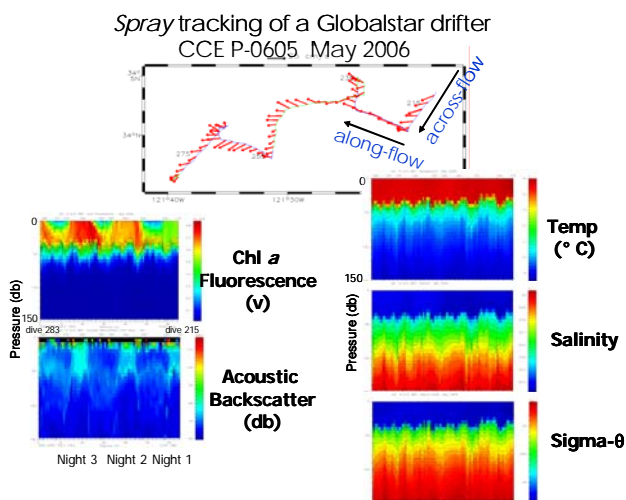

Fig. P2 *Spray* glider tracking of a drift array during P0605, Cycle 1. (UL) Red arrows are mean current velocity, 0-150 m; (L) contours show temp, salinity, density, Chl*a* and acoustic backscatter measured by the glider on 3 successive days and nights. Time advances from right to left in the sections. R. Davis & M. Ohman (unpubl.).

6

backscatter (Night1 to Night 3, right to left) characteristics suggest that we stayed within a single water parcel and probably with the same plankton assemblage. The daily progression in near-surface Chl*a* fluorescence (dives 215-283, right to left) captures the onset of an *in situ* bloom, with glider-estimated specific growth rates of 0.20 d^{-1}. These compare with mean growth rates of chlorophyll of 0.18 d^{-1} measured in our *in situ* drift array incubations over the same time period.

A Moving Vessel Profiler (MVP), purchased on a Moore Foundation grant to Mark Ohman at start of the CCE program, is the workhorse of our ship-based spatial survey work around and between experimental sites. The MVP is a free-fall probe with a computer-controlled winch (**Fig. P3**) that is repeatedly launched and recovered to a depth of 200 m while the research vessel is underway at 11-12 kts. Our instrument contains a rapid-response CTD, a Chl*a* fluorometer and a Laser Optical Particle Counter (LOPC). **Figure P3** shows an example of a "bowtie" pattern from one of the daily 4-h surveys conducted during Cycle 1 on P0605 that illustrates the 3-D structure of the ocean water column in the immediate vicinity of the drift array. The ability to visualize these 3-D ocean sections rapidly in the field has proven to be vitally important for initial selection of experimental sites and for testing assumptions about spatial uniformity and evolving conditions during the time-series Lagrangian experiments.
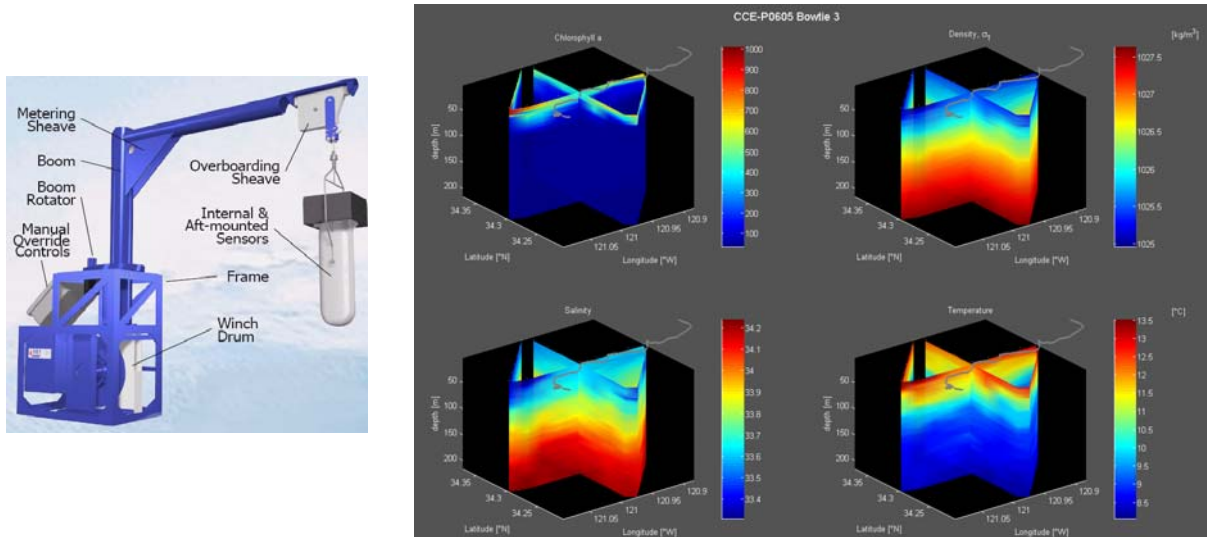

Fig. P3. MVP boom assembly and free-fall fish; launch and recovery of the fish are computer-controlled from inside the ship's lab. MVP 'bowtie' survey plots from Cycle 1 of Process Cruise P0605 illustrate 3-D sections of Chl*a*, temperature, salinity and density. The gray line at the top of each bowtie indicates the position of the drift array. M. Ohman, unpubl.

MVP surveys are typically run in conjunction with flow-through surface sampling using the Advanced Laser Fluorometer (ALF) developed and operated by Alex Chekalyuk (LDEO). This instrument complements the MVP's measurements of subsurface Chl structure with quantitative surface mapping of phycobiliprotein pigments, chromophoric dissolved and particulate organic matter, phytoplankton photo-physiological/nutrient status and bio-optical characterizations of phytoplankton community structure (**Fig. P4**).
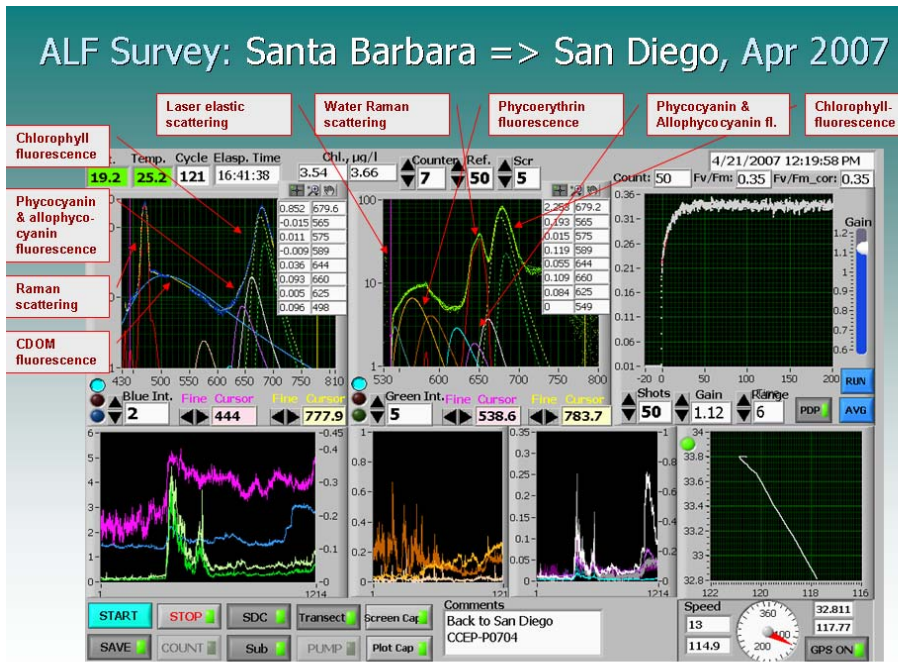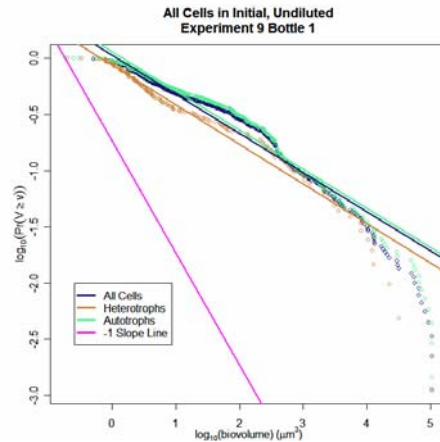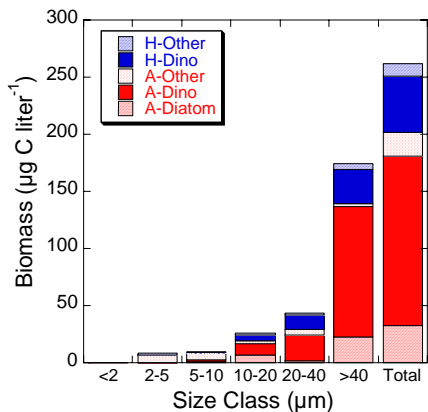
Fig. P4. Real-time spectral deconvolution of hyperspectral ALF measurements of sample emission stimulated with blue and green lasers (upper L and middle panels) and PDP measurements of variable fluorescence, Fv/Fm (upper R panel). Underway distributions of chlorophyll fluorescence, CDOM fluorescence, and Fv/Fm are presented in the lower left panel. Variability in phycoerythrin fluorescence (lower mid-left panel) indicated significant structural changes in the phycobiliprotein-containing algal community (cryptophytes, "oceanic" and "coastal" cyanobacteria). Lower right: GPS track of the ship. A. Chekalyuk, unpubl.

Both CCE process cruises to date have also utilized Cabell Davis' Video Plankton Recorder II (VPR II) system to good advantage. The video imaging capabilities of this profiling towed vehicle have principally been used on long transect runs between study sites and thus highlight the spatial relationships among organisms and physical structure of the water column. This information will be useful in interpreting the raw size-class data from the MVP optical plankton counter and for putting experimental results (e.g., feeding studies with zooplankton) into a spatial context. It is important to note in this regard that the current experimental design of process studies places a premium on sites that are relatively uniform in the mesoscale so that results are not confounded by interference and interactions across strong frontal gradients. At the same time, however, these powerful new tools are allowing us to develop our insights about biological organization in the vicinity of sharp physical features, which may be productivity "hot spots" of interest for future experimental study.

Community Organization and Size Relationships

Though not initially a major focus of CCE experimental studies, size has become a strong organizational theme for community structure, ecological interactions, and modeling. This is not entirely unexpected, given that size theory is relatively well developed for aquatic ecosystems. In the present case, we arrive at this organizational framework partly by parallel development of compatible size-based analytical techniques and a new modeling framework. However, our initial focus and continuing interests are taxon-specific (functional group to species level), since it is relatively easy to work from taxonomic categories to size analysis, but not vice versa.

Mike Landry and new grad student (former tech) Andrew Taylor have developed a largely automated, epifluorescence microscopy imaging system to facilitate analyses of microbial components of the plankton community (auto- and heterotrophs < 200 µm). As illustrated in **Figure P5 (left)**, the products of these analyses can be viewed conventionally as abundance or biomass contributions of varying taxonomic groups in defined size categories; this particular representation emphasizes the relative importance of dinoflagellates and the biomass dominance of larger size fractions. Combined with complementary analyses of pigments and flow cytometry from experimental process studies, such data are the basis for taxon-specific rate estimates of phytoplankton growth and grazing, and for ecological modeling by group or function. The same microscopical analyses, however, can also be viewed statistically as probability distribution functions (size spectra). Data in this normalized biomass

Fig. **P5**. Contrasting representations of plankton community composition from epifluorescence image analysis microscopy (surface mixed layer, P0605, Cycle 1). Left – conventional representation, conveying group contributions within broad size classes. A = autotrophic; H = heterotrophic. Right – probability distribution functions (PDF) of auto- and heterotrophic cells on a log-normalized scale. (Landry, Taylor & Taniguchi, unpubl.)

representation lack taxonomic groupings and emphasize a declining relative biomass of larger cells (**Fig. P5 right**). Grad student Darcy Taniguchi is in the early stages of evaluating how biomass spectra from experimentally manipulated communities (i.e., diluted to reduce grazing interactions) can be used to provide new insights into size-dependent growth and trophic interactions, and whether they can yield a efficient new approach to size-structured ecological modeling.

In parallel developments for larger planktonic organisms, Mark Ohman's lab has been using a novel imaging system to analyze the zooplankton in vertically stratified MOCNESS samples. Replicated day and night samples from each experimental cycle are scanned ashore at 2400 dpi on a digital scanning device ("Zooscan"), resulting in detailed images of individual zooplankters (**Fig. P6A, below**), together with extensive morphometric measurements of each ROI (region of interest). After manual development of a training set of images of known organisms, a confusion matrix is constructed to test the validity of different image analysis algorithms. At present we are obtaining 78-91% accuracy of automated image classification.

Some initial results from the P0605 process cruise obtained by visiting graduate student Jean-Baptiste Romagnan and Ohman suggest interesting differences between copepods and chaetognaths in spatial variability of vertical distributions. For both taxa, larger individuals dwell deeper in the water column (**Fig. P6B**), but copepods and not chaetognaths show size-dependent diel vertical migration (DVM) behavior. Moreover, the amplitude of copepod DVM is considerably greater in the offshore (Cycle 5) than in the nearshore upwelling domain (Cycle 1), probably related to differences in optical transparency and visual predation risk. Long-term changes in optical transparency in the California Current, such as documented by Asknes, Ohman and Rivière (2007, L&O) may therefore alter the vertical distribution of zooplankton and accessibility to predators.
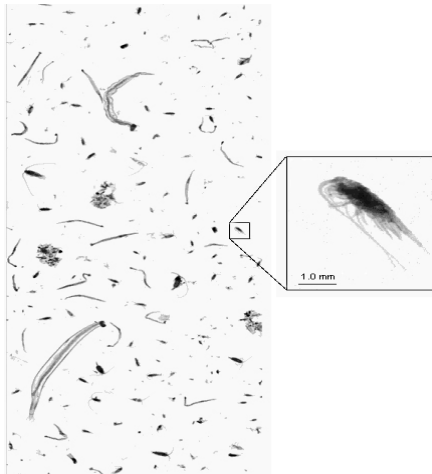

Fig. P6A. Zooscan digital image of a scanned MOCNESS sample from P0605, with inset showing a mature *Pleuromamma* (calanoid copepod).
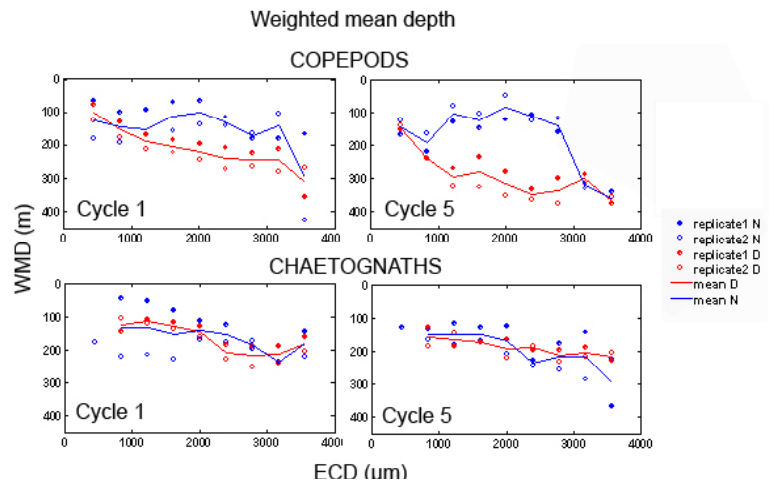

Fig. P6B. Weighted mean depth of (upper) copepods and (lower) chaetoganths, as a function of body size (ECD; equivalent circular diameter). Blue symbols and lines are night samples; red symbols and lines are day samples, for Cycle 1 (nearshore, upwelling) and Cycle 5 (offshore, stratified) on P0605. Romagnan and Ohman, unpubl. .

Mechanisms of Production Control

Iron (Fe) is an essential micronutrient for enzyme systems involved in chlorophyll synthesis, photosynthetic CO_2 reduction, electron transport and nitrate utilization, and is known to limit phytoplankton production and biomass accumulation in several large regions of the open ocean. Recent CCE work has now demonstrated Fe limitation under certain circumstances in our study region. Grad student Andrew King and Kathy Barbeau have shown, for example, that productive upwelling areas are depleted first in Fe, leaving a zone of residual nitrate and Fe limitation on their seaward fringes. Water collected from such areas show the classic diatom-dominated bloom response when Fe is added in shipboard "grow out" experiments (King & Barbeau. 2007). According to King and Barbeau's conceptual model of this phenomenon (**Fig. P7**), the rate of new production is markedly reduced in these areas relative to the nutrient-replete upwelling zone by growth-rate limiting concentrations of Fe.
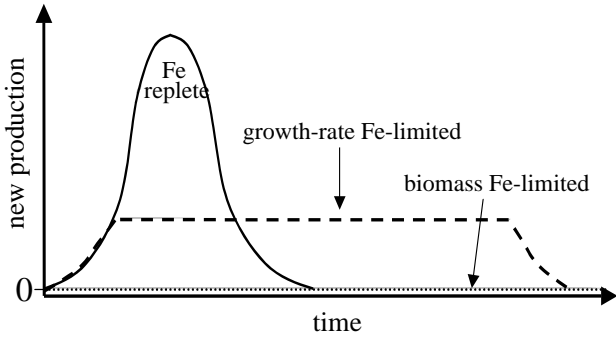
Fig. **P7**. A simplified conceptual model of new production (NP) in 3 scenarios in which initial nitrate concentrations are equal. The solid line (——) represents an iron-replete system, the dashed line (- - -) is a system of Fe-limited growth rate, and the dotted line (·····) represents iron as a biomass-limiting nutrient (e.g., a high-nutrient, low-chlorophyll system). High NP occurs over a relatively short time in the iron-replete scenario, while lower NP occurs over a longer time when Fe is growth-rate limiting. Total NP rates are equivalent in both situations because nitrate limits biomass. (King & Barbeau. 2007. Mar. Ecol. Progr. Ser 342: 91-103)

In additional studies, it has been further demonstrated by graduate student Brian Hopkinson and Kathy Barbeau that Fe-light co-limitation of production also appears to play an important role in strong subsurface chlorophyll maxima (SCM) that typically occur in offshore areas with nutrient-depleted surface waters. A strong response to Fe and light (L) was especially notable in experimental studies with waters from an anomalously strong SCM sampled during Cycle 5 of P0605 (**Fig. P8**). In this and other experiments conducted in the region, observed increases in F_v:F_m and Chl a:POC ratios with iron additions suggest that Fe-light co-limitation is driven by a greater need for iron-containing photosynthetic proteins in low-light environments (**Fig. P9**). Iron additions lead to a shift in the size and taxonomic structure of the phytoplankton community, with large diatoms dominating a formerly diverse assemblage of relatively small phytoplankton. Strong light dependency of the response to added Fe indicates that iron limitation may be especially acute when light levels change rapidly (e.g., with the strong internal wave activity). Iron influences on phytoplankton community structure and production in SCMs therefore have previously unappreciated consequences for nutrient cycling and carbon export from the lower euphotic zone of stratified oligotrophic systems, ocean conditions that are predicted to increase with global warming.
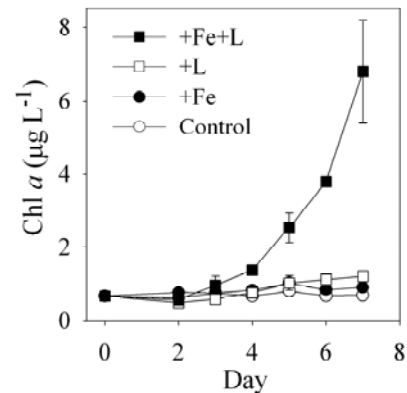

Fig. **P8**. Strong iron-light co-limitation of the eukaryotic phytoplankton community was observed during P0605, Cycle 5. The incubation was initiated with water from an anomalously strong SCM believed to be the result of a previous nutrient input event. (Hopkinson & Barbeau. In review. L&O).
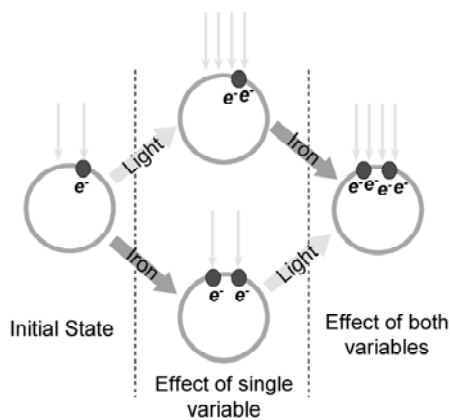
Fig. P9. Conceptual model of iron-light co-limitation due to iron requirements of the photosynthetic system (Sunda and Huntsman 1997). In this state, the ability to process light limits energy generation (represented by electrons: e-) and growth, while the availability of iron limits production of photosynthetic proteins (dark ovals in cell membrane) used to process light. Increasing iron or light individually is expected to increase growth rate, and a synergistic effect should be observed if both variables increase together.

11

In another process cruise study, graduate student Ryan Rykaczewski and Dave Checkley have markedly advanced our understanding of the productivity link between physics and fish in the California Current. Their study notes, for example, that classic coastal upwelling makes a relatively small contribution to total system productivity relative to offshore upwelling due to wind stress curl. Moreover, variability of the latter is strongly related to variability in annual surplus production of the Pacific sardine, a major climate-responsive species in the study region. Research conducted on the CCE processes cruises contributed significantly to the interpretation of these results by demonstrating a strong relationship between upwelling intensity from wind stress curl and the size of zooplankton available as sardine prey (**Fig. P10**).
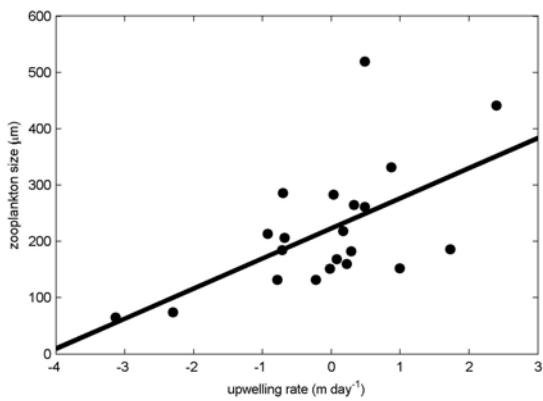

Fig. P10. Relationship between mean zooplankter size and upwelling vertical velocity.   Size was measured at stations across the CCE during P0605. Upwelling rates were determined from winds measured remotely and with a shipboard anemometer. Correlation between mean zooplankter size and upwelling rate is significant (R = 0.58, p < 0.01, n = 21). (Rykaczewski & Checkley, in review).

SCALES OF ECOSYSTEM VARIABILITY: Time Series Programs

The time series research of the CCE site has various components. A key element is CCE augmentations to the quarterly CalCOFI cruises, in order to characterize low frequency variations in ecosystem state, address our key hypotheses, and sustain measurements of the core LTER variables (*Pattern and control of primary production*; *Spatial and temporal distribution of populations selected to represent trophic structures*; *Patterns of inorganic inputs and movements of nutrients*; and *Patterns and frequency of disturbances*). Other time series elements to our site include satellite remote sensing (temperature, Chl*a*, primary production, and export production; Greg Mitchell and the Scripps Photobiology Group); ocean glider-based measurements (Russ Davis and Mark Ohman); deep-sea benthic fluxes (Sta. M program, Ken Smith lab); and the Scripps Pier and the Dana Point Ocean Institute coastal oceanographic time series.
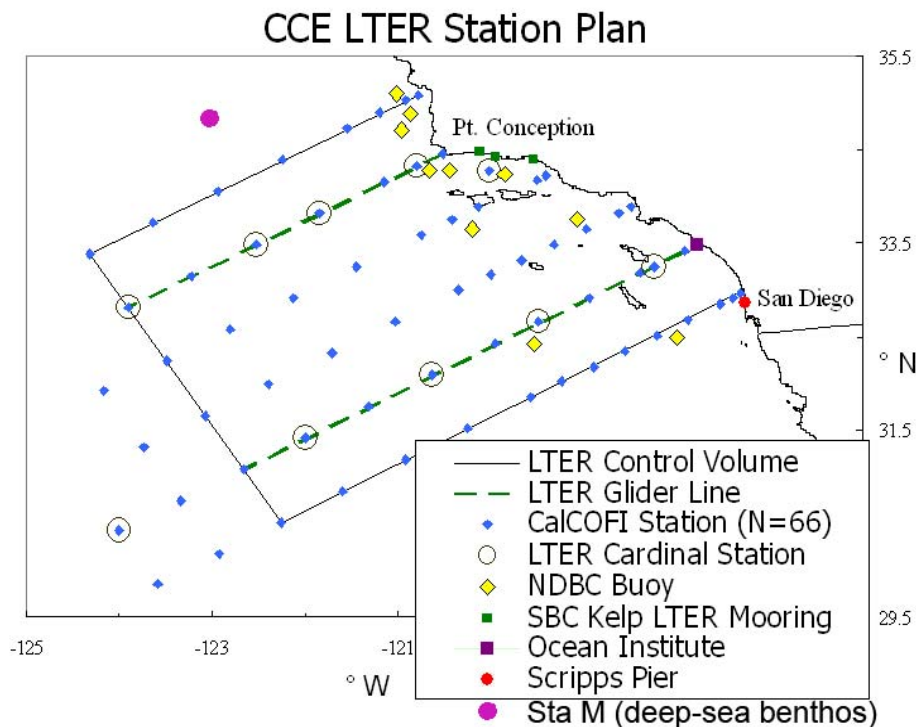

Fig. T1 Blue diamonds indicate the 66 standard CalCOFI stations, all of which are sampled by CCE at 3 depths. In addition, at the 10 CCE-cardinal stations full 8-depth profiles are collected. The control volume region is delineated by solid gray lines. *Spray* gliders are continuously operating along lines 80 and 90. The two coastal stations are the Dana Point and Scripps Pier stations, at the inshore ends of lines 90 and 93, respectively.

CalCOFI/LTER Cruises

To date CCE investigators and technicians have participated on 12 Augmented CalCOFI cruises. The cruises cover 66 to 75 stations off Southern California (**Fig. T1**). On these cruises the Scripps CalCOFI group records basic hydrographic and environmental variables and measures concentrations of dissolved oxygen, inorganic plant nutrients, and Chl*a*. The

Southwest Fisheries Science Center (SWFSC) CalCOFI group deploys a variety of plankton nets to collect samples of macrozooplankton, fish eggs and fish larvae. All measurements are made to an extremely high technical standard. Sampling by CCE technicians on these cruises seeks to further characterize (1) the biological communities of the CCE and (2) key aspects of the biogeochemical system. In addition, (3) CCE-LTER investigators or associates carry out other research programs that directly contribute to the goals of the CCE-LTER program.

1. Measurements belonging to the first category are flow cytometry for the enumeration of bacteria and picoautotrophs, chemotaxonomic analysis of the phytoplankton community using taxon-specific pigments, size fractionation of Chl*a* as a proxy for phytoplankton community size structure, enumeration of nano- & microplankton via automated epifluorescence microscopy, enumeration of mesozooplankton sentinel species via microscopy and broader taxonomic categories via optical scanning and image analysis, and depth profiles of particle/plankton abundance and size structure using a Laser Optical Plankton Counter (LOPC).

2. Measurements belonging to the second category include analysis of upper ocean currents using ADCP, concentrations of ammonia, dissolved organic carbon and nitrogen, particulate organic carbon and nitrogen, concentration of iron, and rates of production of dissolved organic matter.

3. CCE-LTER investigators or associates make measurements of surface layer and air pCO_2 continuously (Friedrichs & Chavez, MBARI), bio-optical measurements to characterize the light and particle environment of the system (Goericke, SIO), enumerate marine mammals along cruise tracks visually and acoustically (Hilderbrand, SIO), and enumerate seabirds visually (Sydeman, PRBO).

Below are descriptions of measurements and results for selected research projects carried out as part of the Augmented CalCOFI-CCE cruises. They are organized somewhat artificially under the headings:

Long-term variability in the pelagic ecosystem

Mechanisms underlying ecosystem variability

although in reality the former cannot be separated from the latter.

Long-term variability in the pelagic ecosystem

The 20th century warming of the California Current: A paleo perspective

David Field, then a graduate student working with Mark Ohman and Chris Charles (and now a postdoc at UCSC), analyzed the paleosedimentary record of fluxes of tests of planktonic foraminifera from the Santa Barbara basin over the past 1400 years. The sediment-based record was complemented by a detailed analysis of the water column habitats of extant planktonic foraminifera through an extensive series of Mocness tows across the California Current.

A major finding from the study was a pronounced increase in fluxes of subtropical forams in the middle 20th century (**Fig. T2**, Field et al. 2006. *Science*). Kasten core records revealed that two of three species showed fluxes unprecedented in the past 1400 years, corresponding to warmer ocean conditions in the California Current than have occurred at least within the past millennium. Complementary box core records showed that not only have subtropical species increased, but cool/temperature species have decreased, beginning in the mid twentieth century. This marine 'hockey stick' curve suggests that the pelagic food web has already undergone significant perturbations in response to ocean warming, largely of anthropogenic origins.
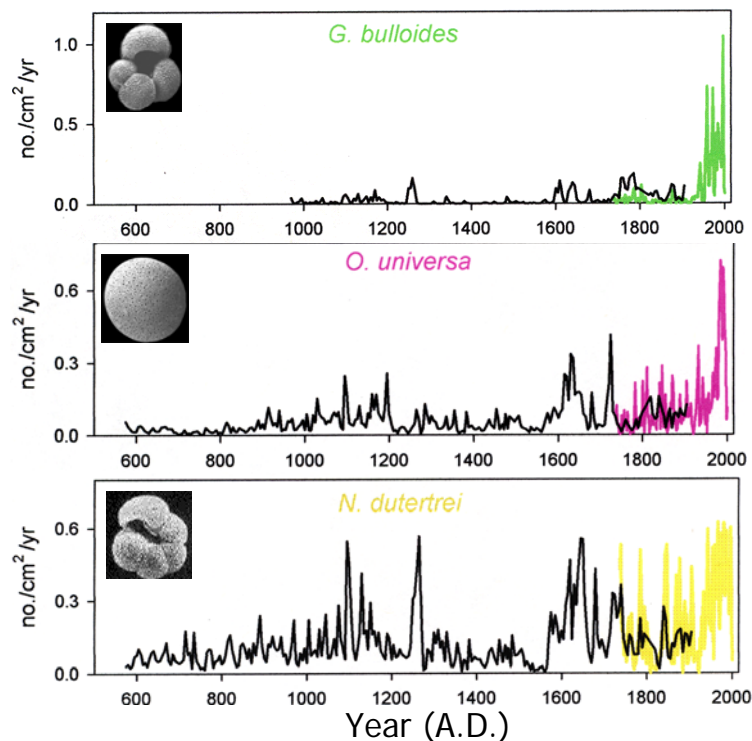

Fig. T2. Flux of 3 species of subtropical planktonic foraminifera from a Kasten core of Santa Barbara basin sediments (Field et al. 2006. *Science* 311:63).

Effects of fisheries on population variability and extinction risk

Then graduate student (now Assistant Professor) Chih-hao Hsieh, working with George Sugihara, John Hunter, and others, analyzed the unparalleled ichthyoplankton record from the CalCOFI time series, now in its 57th year. This exceptional record encompasses up to 400 species of fish eggs and larvae, many described by Southwest Fisheries Science Center scientists for the first time. Hsieh et al. compared the characteristic variations of a suite of exploited species over time with the dynamics of a 'control' group of unexploited species. The remarkable result was that the exploited species consistently showed higher year-to-year variability than the unexploited species, even after correcting for the effects of age at maturation, phylogeny, and other constraints (**Fig. T3**). This effect comes about through a fishery-induced truncation of age structure of the population, which removes the largest and most fecund size classes that contribute disproportionately to recruitment and modulate the effects of environmental variability. This phenomenon, destabilization of populations through harvesting, is another important source of anthropogenic influence on ecosystem variability. It has significant implications for the management of marine resources not only in the California Current, but around the globe. The results were published in *Nature* (2006, 443:859-862).
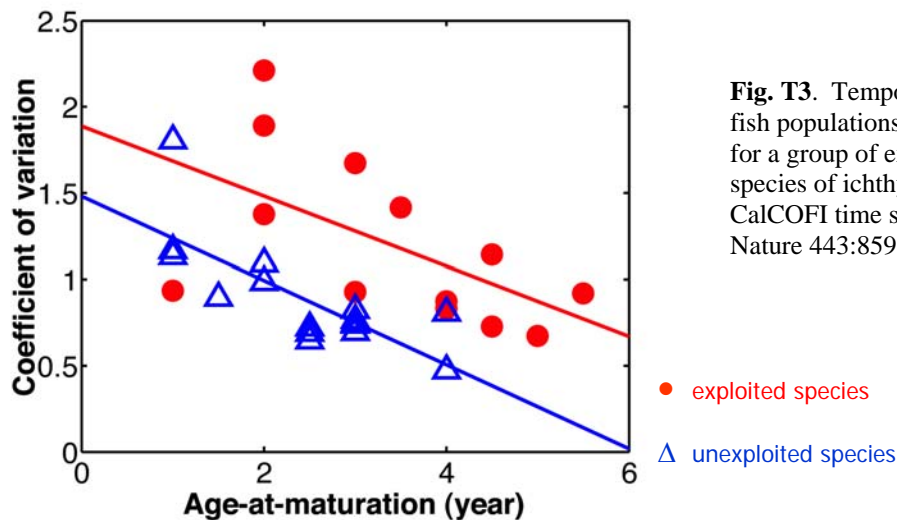

Fig. T3. Temporal variability (C.V.) of fish populations vs. age-at-maturation, for a group of exploited and unexploited species of ichthyoplankton from the CalCOFI time series (Hsieh et al. 2006. Nature 443:859)

● exploited species

△ unexploited species

Variability of the California Undercurrent

Peter Gay and Teri Chereskin have investigated the magnitude, location and extent of the California Undercurrent off Southern California using CalCOFI data from 1993 to 2003, which provide hydrographic, biochemical, wind and water velocity data on a quarterly basis together with sea-levels based on satellite altimetry. The driving mechanism for the undercurrent off Pt. Conception and the Santa Rosa Ridge appears to be a combination of poleward pressure gradients and local wind-stress curl. The poleward flow in the Southern California Bight is less influenced by regional pressure gradients but is affected by the California Current recirculation in the Southern California Eddy, and the influence of the islands, channels and basins making up the Southern California Bight. The inshore poleward flow between 100 m and 400 m depth is primarily composed of a surface intensified flow with semi-annual variability, having peaks in both spring and fall, and a depth-independent part with a single annual peak in fall. Grouping the data by season and pentade shows that the undercurrent is strongest following the weakening of seasonal coastal upwelling and during El Nino-influenced years (**Fig. T4**).

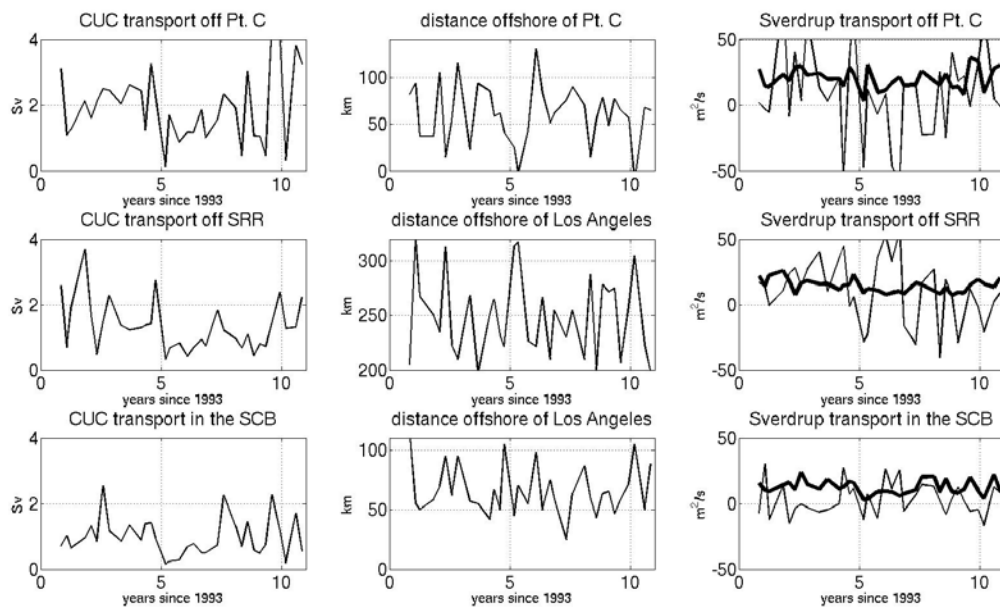**Fig. T4**. Time-series of estimated CUC transport between 100 m and 400 m depth (left), distance offshore (center) and transport/width for comparison with Sverdrup transport based on the wind-stress curl over the region of the model CUC (right). In the right-hand plots the thick line represents the model CUC and the thin line represents the Sverdrup transport based on the wind-stress curl. Error = 0.1. (Gay and Chereskin, in prep.)

Variability of properties of the California Undercurrent

Complementary to the Gay and Chereskin analyses of variations in the magnitude and location of the California Undercurrent, Steven Bograd has analyzed long-term variations in the dissolved constituents at Undercurrent depths. Such changes have particular ecological significance because Undercurrent depths are likely source waters for upwelling into the euphotic zone. There are trends over the past 22 years in various water properties at two density levels (25.6 - upper thermocline, 26.4 - deeper thermocline and California Undercurrent) at CCE-LTER (CalCOFI) station 93.30, which is strongly impacted by the CUC. Other CalCOFI stations show similar, but less significant, trends. There are significant trends in spiciness, apparent oxygen utilization, and the inorganic nutrients nitrate, phosphate, and silicic acid (**Fig. T5**). The differing rates of change in nutrient content is leading to large decreases in mid-thermocline ratios of dissolved N:Si. These trends reflect apparent shifts in the quantity or properties of source waters to the CCE-LTER, with possible impacts on upstream and near-surface ecosystem structure.
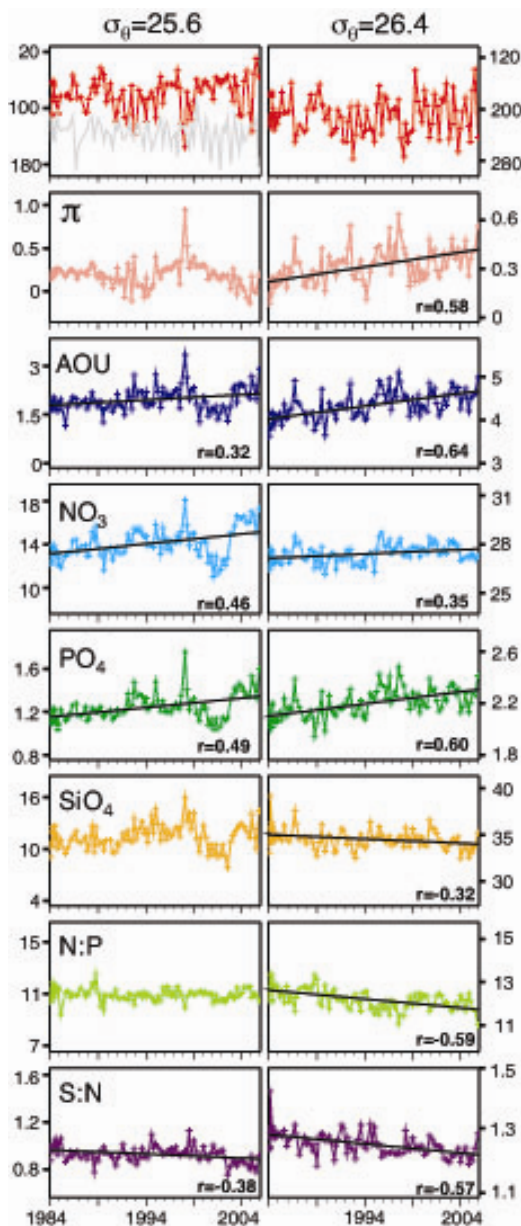
Fig. T5. Water property time series at station 93.30, 1984-2005, on the sq = 25.6 kg m-3 (left panels) and sq = 26.4 kg m-3 (right panels) isopycnal surfaces. From top to bottom, isopycnal depth (m), spiciness (kg m-3), apparent oxygen utilization (mL L-1), nitrate (mMol kg-1), phosphate (mMol kg-1), silicate (mMol kg-1), nitrate:phosphate ratio, and silicate:nitrate ratio. Significant linear regressions (p < 0.001) are shown with black lines. The dashed gray line in the top left panel is the depth difference (m) between the sq = 26.4 kg m-3 and the sq = 25.6 kg m-3 isopycnal surfaces. (Bograd, unpubl.)

18

Temporal changes in silicic acid concentrations in the CCE

Ralf Goericke's analyses indicate that silicic acid anomalies observed during 2003 to 2006 are the lowest on record (**Fig. T6A**). These large negative silicic acid anomalies coincided with large negative salinity anomalies, suggesting that the former are directly or indirectly related to the increased transport of subarctic waters into the CCE area.

These changes in silicic acid concentrations likely affected diatom growth. The half saturation constant for silicic acid uptake by diatoms is for most of these in the range 2 to 3 µM. Whereas prior to 2003 only 9 % of all stations with mixed layer nitrate concentrations larger than 0.3 µM had silicic acid concentrations < 2.5 µM, after 2003 52 % of all stations were in that category (**Fig. T6B**). For comparison, during 1984 to 1987 the value was 19%. These data imply that the likelihood that diatom growth was limited in recent years by the availability of silicic acid was increased by about a factor of five.

We plan to test the hypothesis arising from these data by comparing phytoplankton community structure between 2004 and 2006 with community structure after 2006. The hypothesis predicts a decreased abundance of diatoms, for comparable levels of total phytoplankton biomass.

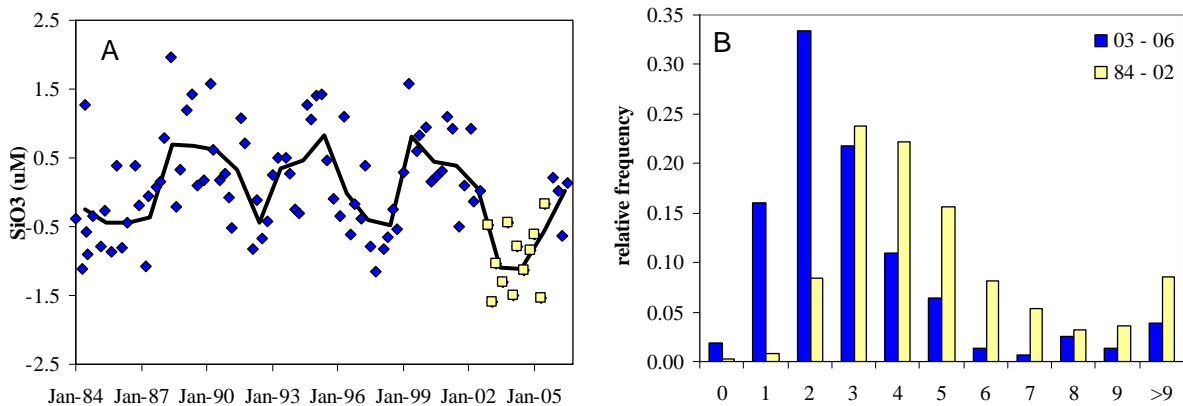**Fig. T6 A.** CalCOFI region anomalies for mixed layer silicate. Symbols represent averages of individual cruises. Annual averages are represented by the solid line. **B.** Normalized ML Silicate concentration frequencies for CalCOFI stations with nitrate concentrations larger than 0.3 µM. blue bars are frequencies for 2003 - January 2005. Open bars are for 1984 to 2002. Note the dramatic shift in the frequency distribution.

19

Estimating net primary production from remotely sensed ocean color

Net primary production (NPP) is an important component of the carbon cycle in the California Current System (CCS) and important quantity for cross-site comparisons within LTER. Accurate quantification of the carbon cycle components at regional and global scales is required due to the impact of carbon on climate change. In situ measurement of NPP from ships is highly time consuming and unreliable due to large space and time variability. Satellite methods hold promise but current algorithms are not accurate enough. **Figure T7** shows time series of NPP in two selected domains in the CCS as estimated by Greg Mitchell and Mati Kahru, using two state-of-the-art NPP algorithms, the standard VGPM algorithms (Behrenfeld and Falkowski, 1997) and the new, carbon-based productivity algorithm (CbPM, Behrenfeld et al., 2005). Differences of up to 100% are not uncommon between these NPP estimates and systematic differences are obvious. Compared to VGPM estimates, the CbPM estimates are generally lower in the north and higher in the south but the temporal dynamics can be in the opposite phase. More work is urgently needed for improving the NPP algorithms and the CCS is an ideal laboratory for these studies.

The satellite data archive is available from http://spg.ucsd.edu/Satellite_data/California_Current/.
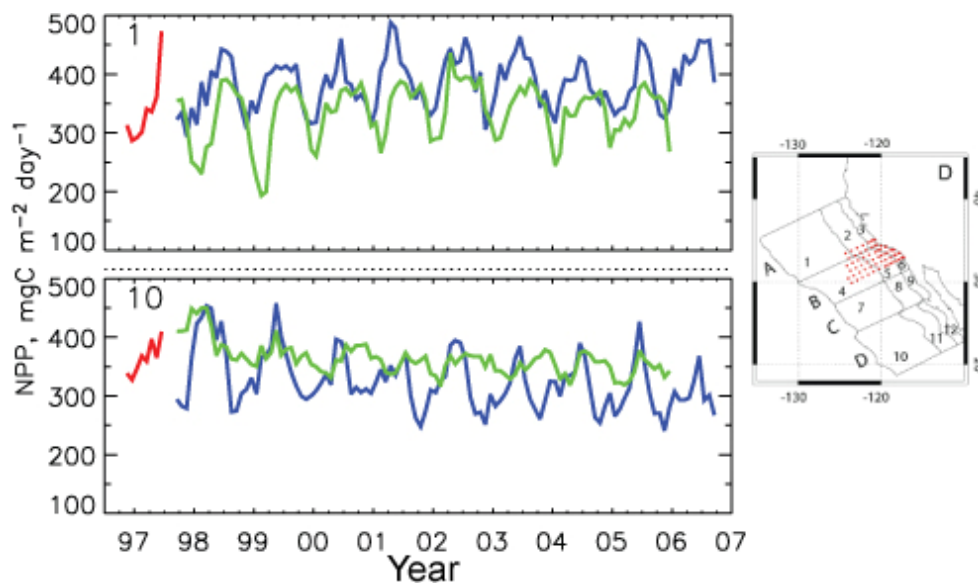
Fig. T7. Time series of net primary production (NPP) estimated in domains 1 and 2 (shown in the inset) using two current algorithms, VGPM (red and blue) and CbPM (green). The satellite data are from OCTS (red) and SeaWiFS (blue and green)

Behrenfeld, M.J., and P.G. Falkowski (1997), Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnol. Oceanogr.* 42, 1-20.
Behrenfeld, M.J. et al. (2005) Carbon-based ocean productivity and phytoplankton physiology from space, *Global biogeochemical cycles*, 19, GB1006, doi:10.1029/2004GB002299.

Deep-Sea benthic POC fluxes estimated from satellite-derived primary productivity

　　　Ken Smith's lab has analyzed particle fluxes to the deep sea benthos at Sta. M, located just on the periphery of our water column sampling program, in relation to climate indices and satellite-based estimates of near-surface primary production. Together with former graduate student Henry Ruhl (now a postdoc at MBARI), and CCE remote sensing colleagues Greg Mitchell and Mati Kahru they have successfully modeled interannual variations in POC fluxes. A long time-series study was conducted over 15 yr (1989–2004) to measure particulate organic carbon (POC) flux as an estimate of food supply reaching 4,000-m depth in the northeast Pacific. Sequencing sediment traps were moored at 3,500-and 4,050-m depth, 600 and 50 m above the seafloor, respectively, to collect sinking particulate matter with 10-day resolution. POC fluxes were compared with three climate indices in the Pacific: the basinscale multivariate El Niño index (MEI), the northern oscillation index (NOI), and the regional scale Bakun upwelling index (BUI). The NOI and MEI correlated significantly with POC flux, lagged earlier by 6–10 months, respectively. The BUI also correlated with POC flux, lagged by 2–3 months, suggesting a direct relationship between upwelling intensity and rates of POC supply to abyssal depths. Satellite ocean color data for the surface above the study site were used to estimate chlorophyll *a* concentrations and, combined with sea surface temperature and photosynthetically available radiation, to estimate net primary production and export flux (EF) from the euphotic zone. EF was significantly correlated with POC flux, lagged earlier by 0–3 months. An empirical model to estimate POC flux, with the use of NOI, BUI, and EF, yielded significant agreement with measured fluxes (**Fig. T8**). Modeling of deep-sea processes on broad spatial and temporal scales with climate indices and satellite sensing now appears
feasible.

Climate effect on deep-sea ecosystems
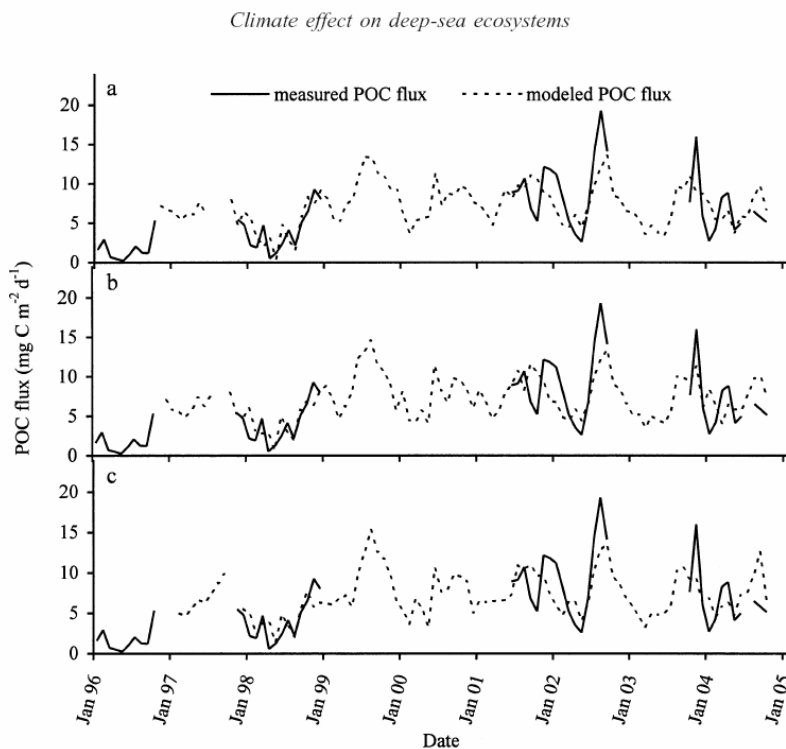
Fig. T8. Empirical model results for POC50 mab flux with the use of temporally lagged BUI, NOI, and export flux (EF) over the period from November 1996 through October 2004 for each of three catchment areas centered over Sta. M compared with the measured POC50 mab flux for a catchment area of (a) 50-km radius circle ($r[s] = 0.73$, $p < 0.001$, $n = 42$), (b) 100-km-radius circle ($r[s] = 0.70$, $p < 0.001$, $n = 42$), and (c) 600- X 200-km oval ($r[s]=0.70$, $p<0.001$, $n = 41$). From Smith et al. 2006 (L&O 51:166-176)

Scales of variability in the CCS revealed by mesozooplankton

The long-term record of mesozooplankton variability in the CCE site is especially well developed, thanks to the continuity of CalCOFI sampling and support for plankton sample analysis, first through U.S. GLOBEC and then CCE-LTER. A recently completed analysis by Mark Ohman and his former postdoc Bertha Lavaniegos (2007, in press, Prog. Ocean.) has revealed that the scales of ecosystem variation detectable in the zooplankton are highly dependent upon the level of taxonomic analysis conducted and also the metric of biomass used. For example, mesozooplankton biomass expressed as organic carbon shows no long-term trend over the 56-yr record, in marked contrast to the continued decline observed in displacement volume (**Fig. T9** mid vs. upper). The discrepancy between these measures of biomass arises because of a long term decline in pelagic tunicates, especially salps (**Fig. T9** lower), which have a very high ratio of biovolume:organic C. The biomass of pelagic tunicates is inversely related to water column density stratification (**Fig. T10**) and thus, as the surface ocean continues to warm and stratification increases, we expect a decreased contribution of pelagic tunicates (especially salps) to
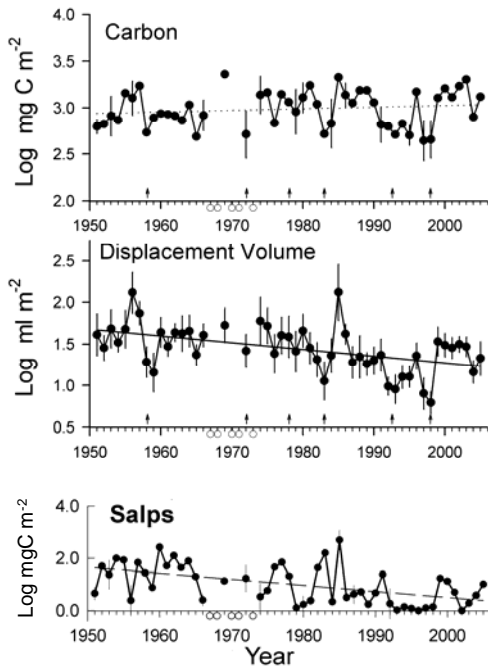

Fig. T9 Long term changes in mesozooplankton biomass as (top) total organic C, (middle) total displacement volume, and (bottom) salps. Upward arrows indicate El Nino years. Lavaniegos and Ohman (2007)
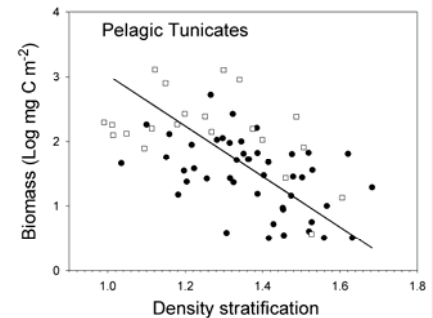
Fig. T10 Relationship between pelagic tunicate C biomass and density stratification (Lavaniegos and Ohman 2007)

the mesozooplankton community. Based on comparisons with Ken Smith and Henry Ruhl's deep-sea benthic flux data, this long-term change in salps is expected to have major consequences for biogeochemical fluxes in the deep sea in the California Current. Note that there are El Nino-related dips in C biomass and displacement volume (**Fig. T9,** upper and mid, small black arrows) but no evidence for an "ecosystem shift" in either metric in the mid-1970's.

In contrast, species-specific analyses reveal distinctive multidecadal variations. E.g., the euphausiid *Nyctiphanes simplex* shows a major shift upward in abundance in the mid-1970's and a decline in 1999 (**Fig. T11,** lower right). The mid-1970's shift was associated with a change in the PDO (upper right), but this relationship changed after 1999.

Fig. T11 Long term variation in (upper rt) the PDO index, (lower left) *N. simplex* biomass, and (lower rt) *N. simplex* biomass

Seabird response to ocean variability – On colonies

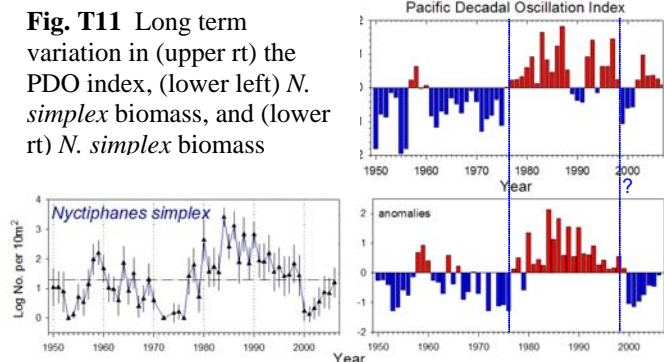The catastrophic breeding failure of Cassin's Auklet off the Farallon Islands in spring 2005 (Fig. 1) led Bill Sydeman, Mark Ohman, and others to examine the variability of euphausiids (krill) in two regions of the California Current. Two species of euphausiids in particular, *Euphausia pacifica* and *Thysanoessa spinifera*, are key prey items for auklets that typically breed in Central California waters. The CCE investigators found that the breeding failure of auklets off Central California, during the spring 2005 period of anomalously delayed upwelling (**Fig. T12**, was accompanied by anomalously low abundances of the two essential species of euphausiids in Central California (**Fig. T13,** note log scale). In contrast, the same two euphausiid species were at or slightly above the long-term mean abundances in southern California waters, CCE region. At the same time, CalCOFI seabird data revealed anomalously high abundances of Cassin's Auklets in the southern California region at the time of breeding failure in the north. This result suggested that the Auklets undertake migrations several hundred km long to utilize more suitable feeding grounds when ocean conditions become unfavorable, even if it means sacrificing breeding opportunities.

Seabird Response to Ocean Variability - On Colonies
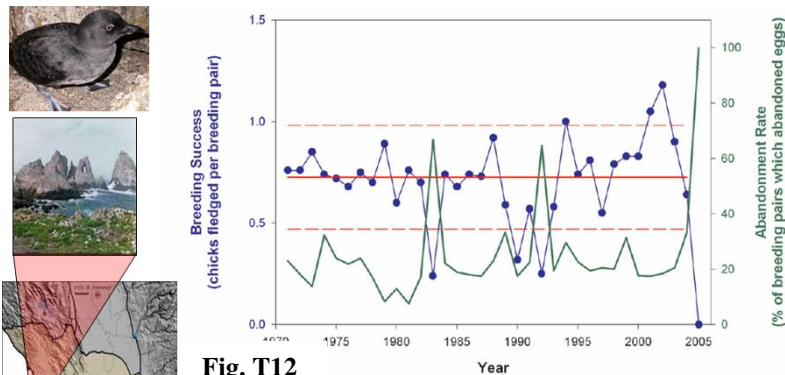
Fig. T12
Interannual variability of Cassin's Auklet breeding success and abandonment rate at Southeast Farallon Island, central California (1971-2005), showing the long-term mean breeding success (solid red line) ± 80% confidence intervals (dashed red lines)

(Sydeman et al. 2006)

CENTRAL CALIFORNIA

SOUTHERN CALIFORNIA
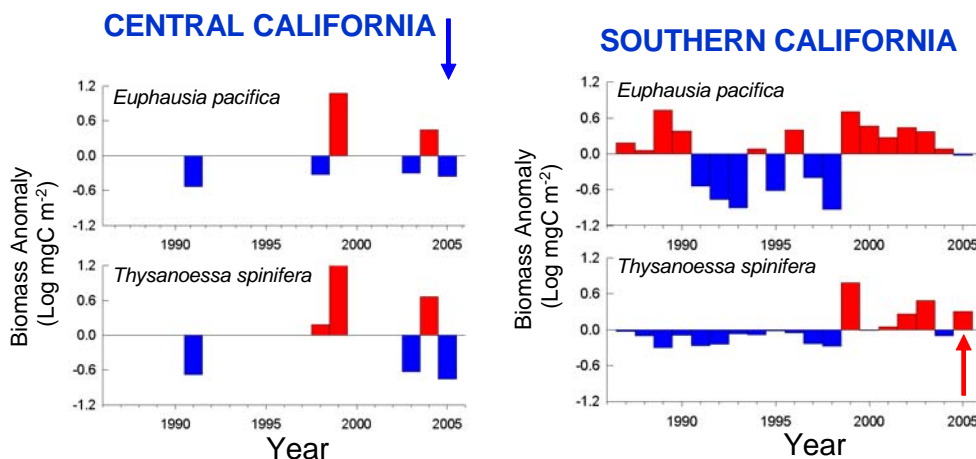
Fig. T13 Anomalies of springtime C biomass of two species of euphausiids (*E. pacifica* and *T.spinifera*) in (left) Central California and (right) Southern California, CCE region. Arrows indicate the spring 2005 breeding failure of Cassin's Auklets off Central CA (blue arrow), simultaneously with the elevated Auklet abundances and krill biomass off S. CA (red arrow). Sydeman et al.(2006)

Seabird Response to Ocean Variability – At Sea
Spring (March – April) CalCOFI Cruises: 1987 - 2004
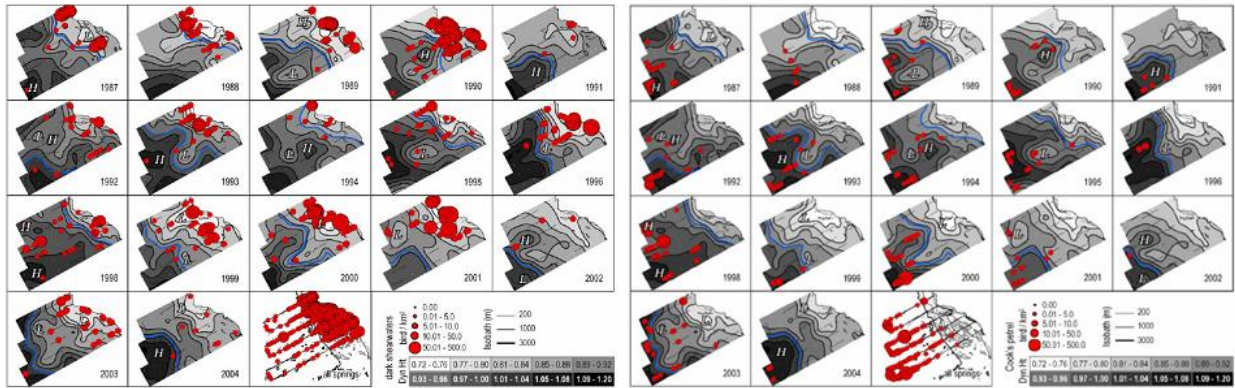
Sub-Arctic Species – Sooty Shearwater

More common in the northern part of the study area, in areas of low dynamic height and high Chl-a

Sub-tropical Species – Cook's Petrel

More common in the southern part of the study area, in areas of high dynamic height and low Chl-a

(Yen et al. 2005)

Fig. T14 Sooty Shearwater (left panel) and Cook's Petrel (right panel) distribution and abundance overlaid on dynamic height contours with the core of the California Current (blue line) over 17 years, 1987–2004. Note that the last panel shows distribution and abundance combined for all years.

David Hyrenbach and collaborators (Yen et al. 2006. Deep-Sea Res. II 53:399) used the 17-year long time series of seabird observations on CalCOFI-CCE cruises to explore associations (presence/absence and density relationships) of marine birds with mesoscale features (eddies, current jet) and metrics of primary productivity (chlorophyll a and nitrate concentrations). Cook's petrel (see **Fig. T14**) was found offshore with no specific habitat affinities. Black-footed albatross, red phalarope, and Leach's storm petrel were found in association with offshore eddies and/or the core of the California Current, but the functional relationship for these species varied, possibly reflecting differences in flight capabilities. The more coastal species, including the shearwaters (**Fig. T14),** fulmar, and red-necked phalarope, were positively associated with proxies of primary productivity. Of the hydrographic habitats considered, the upwelling region of Point Conception appears to be an important ''hotspot'' of sustained primary production and marine bird concentrations. Point Conception and other similar coastal locations (upwelling cells) may warrant protection as key foraging grounds for seabirds (adapted from Yen et al. 2006).

Mechanisms underlying ecosystem variability

Total Organic Carbon and Total Nitrogen

The goal of Lihini Aluwihare's lab within the context of CCE-LTER is to quantify and characterize the organic carbon and organic nitrogen dynamics of the upper ocean. They focus primarily on dissolved organic matter (DOM) and identifying the mechanisms by, and timescales on which this reservoir interacts with other carbon pools in the region.

**Figure T15A** shows total organic carbon (TOC) concentrations in the upper 500m of the water column (plotted as density) along Line 93 during 2005. Overall trends showed the addition of TOC in surface waters (low density) between April and July. The addition was most prominent at nearshore stations. At many stations the concentration of TOC in surface waters decreased from summer to fall indicating both degradation (e.g., the circled region of **Fig. T15A**) and mixing (points enclosed in open squares in **Fig. T15A** show variations in TOC concentration at one surface site over three seasons).
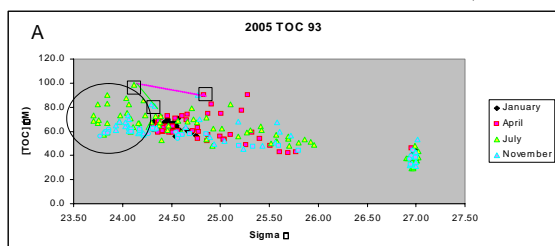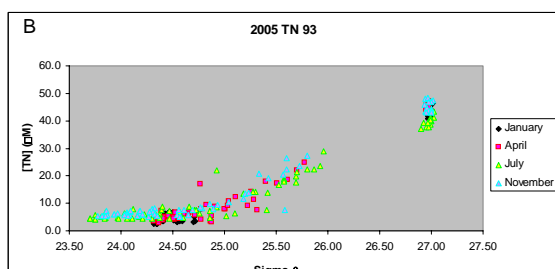
In contrast to TOC concentrations, total nitrogen (TN) concentrations in surface waters show little seasonal variability (**Fig. T15B**, where TN includes dissolved organic nitrogen (DON), dissolved inorganic nitrogen (DIN) and particulate organic nitrogen) As TN is primarily present as dissolved organic N in surface waters (DON) the lack of significant variability implies little to no seasonal accumulation of DON in the surface ocean.

Fig. T15. (**A**) Total organic carbon (TOC, μM C) concentrations along Line 93 and (**B**) total nitrogen (TN, μM N) concentrations along line 93 in the CalCOFI region (2005) as a function of density (sigma-θ).

Isotopic analyses revealed that at least two dissolved carbohydrate fractions followed the Δ^{14}C signature of POC and DIC, confirming the recent addition of DOC to the surface ocean in our study site (**Table T1**, Roman DeJesus and L. Aluwihare, in prep). In contrast, a Δ^{14}C signature of ~ -300‰ was reported for the total DOC reservoir (including dynamic and refractory components) at a station just to the north of station 77.70, suggesting that the DOC reservoir is relatively recalcitrant (Beaupre et al., 2007). Nitrogen isotope signatures confirmed that the accumulating DON reservoir was not replaced on seasonal timescales (data not shown). The seasonal build up of TOC and Δ^{14}C measurements show that organic carbon may be available for horizontal and vertical export from surface waters.

Table T1. Δ^{14}C Signature of Sugars Isolated from Surface Ocean DOC Fractions (CCE-CalCOFI domain)

Surface Ocean Bulk Carbon Reservoirs:
Dissolved inorganic carbon (n=3): 16‰ ± 3‰ to 49‰ ± 4‰
Suspended POC (n=8): 21‰ ± 19‰ (highest value: 50‰ ± 9‰)
Total DOC (n=1) : -303‰ (Beaupre *et al.* 2007)

DOC Carbohydrate Fractions:
Combined glucose + unknown sugar: + 48‰
Combined xylose, rhamnose and galactose: -16‰
Combined fucose +arabinose + mannose: + 21‰

Dissolved Iron in the southern California Current System

The southern CCS has been historically regarded as being a nitrate-limited region. In an effort to investigate the influence of Fe on phytoplankton growth in the southern CCS, graduate student Andrew King and Kathy Barbeau began a time-series study of mixed layer dissolved Fe. Results from Nov 2002, April 2003, and July 2003 CalCOFI cruises (**Fig. T16**) and April 2006/May 2007 LTER Process Cruises (data not presented here) have highlighted the association of high dissolved Fe with the continental shelf and a substantial decline in dissolved Fe >50 km from the coast (**Fig. T17**). In the nearshore region (<50 km), dissolved Fe concentrations were generally higher during fall and spring cruises (circles and x's) as compared to summer (squares; **Fig. T17**). High dissolved Fe near Point Conception, CA was associated with cool and saline (upwelled) water masses. In the offshore region, dissolved Fe was lower in concentration and low in variability during all three seasons. During summer cruises in 2003 and 2004, we found phytoplankton to be Fe-limited at some offshore stations (50-150 km offshore; King and Barbeau, MEPS 342:91-104).
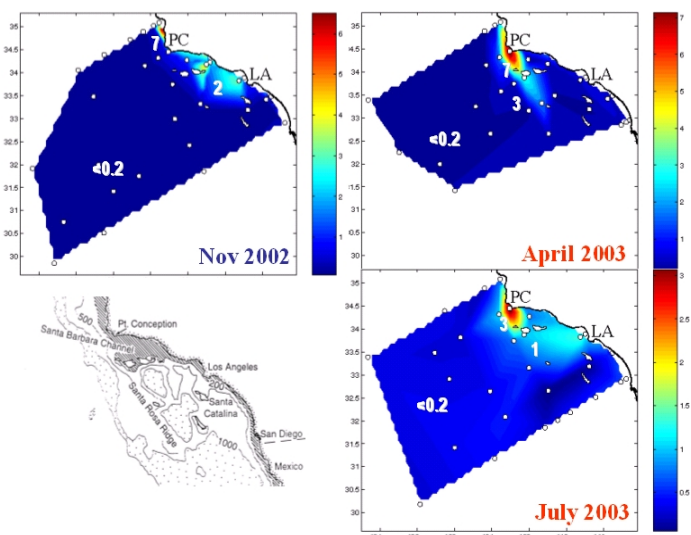
Fig. T16: Upper panels and lower right panel: dissolved Fe concentrations (nmol l^{-1}) in surface mixed layer from CalCOFI cruises during November 2002, April 2003, and July 2003. Data in each plot were interpolated between stations marked with white circles. For geographic reference, Point Conception, California, USA ('PC') and Los Angeles, California, USA ('LA') are labeled in each panel. Lower right panel: bathymetric chart of southern CCS, shaded area marks the extent of the continental shelf (depth <200 m).
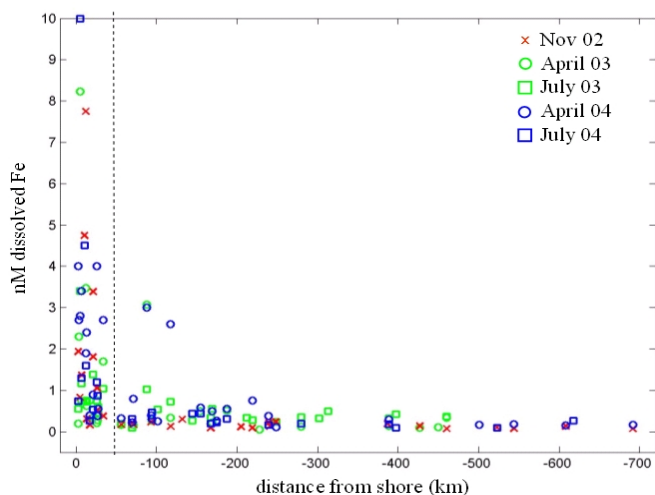
Fig. T17: Dissolved Fe concentrations in surface mixed layer (nmol L^{-1}) plotted against distance offshore (km) from five cruises between November 2002 and July 2004. Note high dissolved Fe concentrations nearshore with notable decrease in concentration >50 km offshore (marked by vertical dashed line)6

26

Phytoplankton community size structure – Do measurements corroborate theory?

An important dimension of phytoplankton community structure is the size distribution of its biomass. More than a decade ago a concept describing how phytoplankton size structure changes with increasing total phytoplankton biomass became popular. Size classes are thought to 'fill up' sequentially, smallest first, and biomass is added to larger size classes only after the smaller ones are filled (Chisholm 1991). This concept predicts that the percent contribution of the smallest size class to total biomass is initially constant – it is the only size class contributing to biomass – but sequentially declines in contributions to the total.

Using size fractionation experiments on all CCE-LTER cruises (GFF, 1, 3, 8, and 20 µm pores sizes), Ralf Goericke found that patterns of biomass in the smallest (< 1µm) size fraction (**Fig. T18A & C**) were as predicted from theory. However, neither the intermediate size classes (**Fig. T18B**) nor the largest size class (> 20 µm) exhibited the predicted patterns. All contributed to varying degrees to total biomass even at very low concentrations of total Chl a. The percent contribution of the 1 to 3 µm size class to total biomass indeed resembled a saw tooth, as predicted, but the contribution of the 3 to 8 µm size class was approximately constant and that of the 8 to 20 µm size class was similar to that observed for the > 20 µm size class.
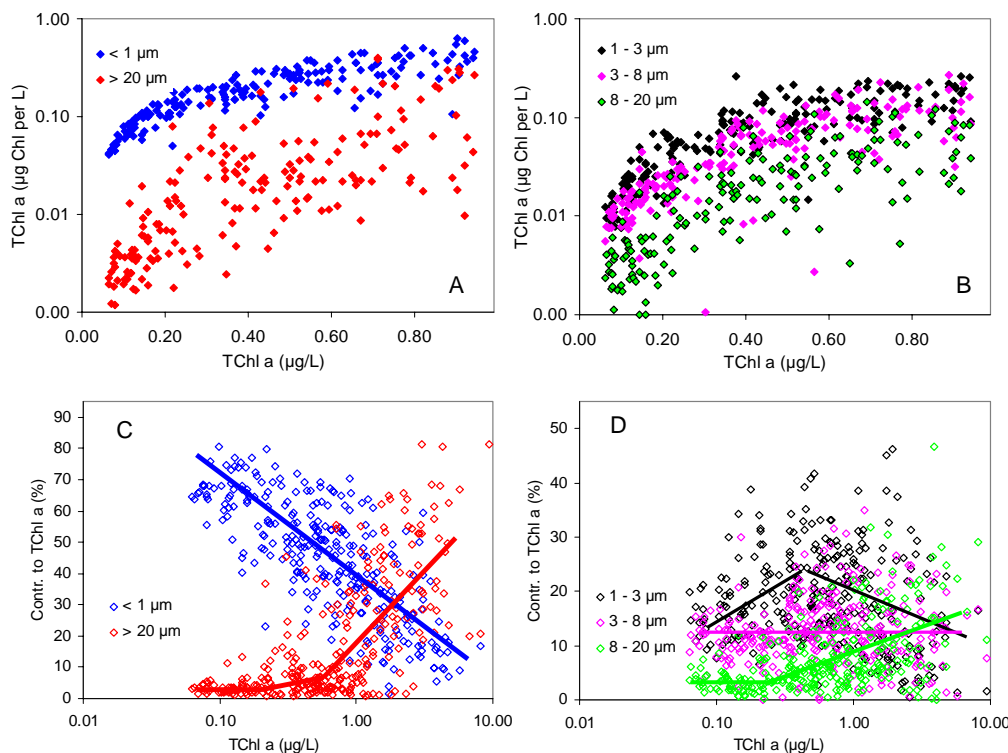
Fig. T18. Results of Chl a size fractionation experiments for 12 CCE-CalCOFI cruise in the California Current Ecosystem. **A** & **B**: Log Chl-Biomass of different size classes plotted against TChl a in the range 0 to 1 µg TChl a. **C & D**: The percent contribution of different phytoplankton size classes (C: < 1 and > 20 µm; D: 1-3, 3-8 and 8-20 µm) to total phytoplankton biomass (µg Chl *a* L-1). The solid lines are idealizations of 20 point running averages. (Goericke, unpubl)

The results from these simple experiments – only 5 size classes were tracked – suggest that the size structure of natural communities cannot be predicted using simple theories which only consider size and size-dependent interactions. It is likely that characteristics other than size are responsible for the observations, notably including characteristics rooted in taxonomic differences among species.

27

Copepod mortality estimation – Spatial trade-offs

Rates of stage-specific mortality are essential to model the population dynamics of key zooplankton species in the CCE pelagic food web. To address the lack of parameter values for this critical term, Mark Ohman and graduate student (and now Assistant Professor) Chih-hao Hsieh applied an inverse Table method to estimate mortality for late developmental stages of the dominant copepod *Calanus pacificu*s. They used the extensive spatial sampling (66 core stations, 20-bottle vertical profiles per station) of the CalCOFI program, including temperature and Chl*a* structure together with detailed stage-structured copepod abundance data, to estimate mortality rates of copepodid stage V/adult males and adult females.

First, they developed a continuous relationship describing the stage duration of *C. pacificu*s as a joint function of temperature and Chl*a* (**Fig. T19**), utilizing previously published laboratory measurements.
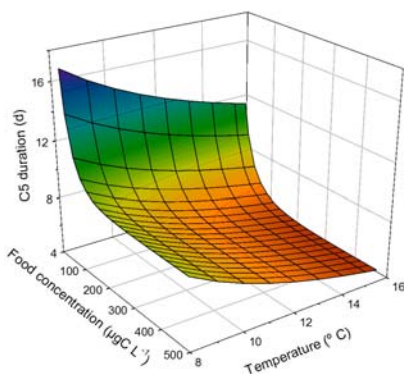
Fig. T19. Stage duration of copepodid stage V of *Calanus pacificu*s as a function of Food concentration and Temperature, derived from a re-analysis of the experiments of Vidal (1980).

They then applied this relationship to estimate spatial patterns of copepod mortality from 7 cruises conducted in the CCE domain. The average spatial pattern of mortality showed consistently elevated values nearshore, in comparison with the offshore sector (**Fig. T20**). Inshore elevation of mortality occurred in spring and fall-winter, for both CV/females and CV/males, across all cruises. Elevated nearshore mortality is associated with elevated nearshore abundances of zooplanktivorous fishes, as assessed from the extensive CalCOFI ichthyoplankton surveys. This result has the important implication that although the nearshore upwelling domain may be a region of elevated food concentrations conducive to high ingestion rates and growth of suspension-feeding copepods, it is also a region of elevated mortality risk. Hence assessments of habitat suitability – and models of population dynamics – must incorporate life history trade-offs and not characterize the environment solely on the basis of food availability or a single habitat characteristic.
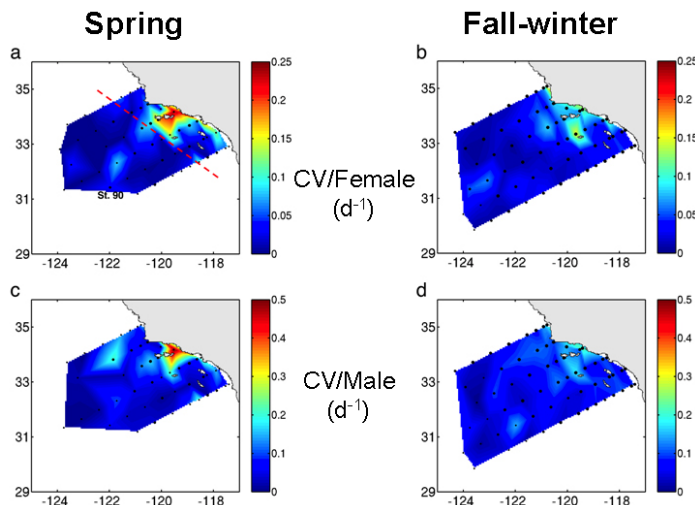
Fig. T20. Average spatial pattern of mortality rate for *Calanus pacificus* in the CCE domain, based on results from 7 CalCOFI cruises (3 in spring (left panels) and 4 in winter-spring (right panels)). Upper panels are joint mortality rates for CV/females, lower panels for CV/males. The dashed red line in the upper left panel separates inshore from offshore stations. Ohman and Hsieh, unpubl.

28

Laser Optical Plankton Counter: Variability of particle/plankton size structure

Since November 2004, Dave Checkley's lab has deployed a Laser Optical Plankton Counter (LOPC) in the mouth of a plankton net (**Fig. T21**) on all CalCOFI/LTER cruises to characterize in situ changes in plankton size spectra in space and time. These data are important for our size-spectrum modeling studies. To date, the LOPC-Bongo has been deployed on 11 such cruises (4 in 2005, 4 in 2006, and 1 in 2007), with profiles from 0-210 m on more than 70 stations per cruise. The following data are from 2005, to illustrate processing and preliminary results.
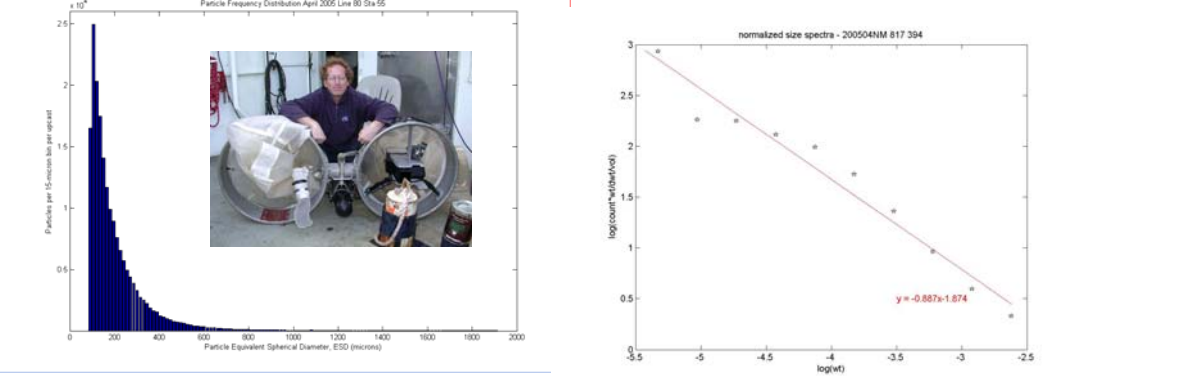
Fig. T21. (a) An LOPC-derived size-frequency distribution for one cast, for particles from 100-2000 μm Equivalent Spherical Diameter (ESD). Inset shows LOPC mounted in one side of the bongo net. (b) A normalized size spectrum, in which the estimated mass of material in $\log_e$ size bins, normalized to the mean mass of the size bin and the volume of water filtered, is plotted against particle size (for a different profile).

The slope of the size spectrum indicates the relative size composition of the sensed particle assemblage, with a more negative (steeper) slope indicating greater importance of small particles. The y-intercept indicates the total mass of particles sensed, with a larger value indicating greater particle mass. **Figure T22** shows LOPC data from the Spring 2005 CalCOFI/LTER cruise. The spectrum slope is shown on the left and y-intercept on the right, with quartiles color-coded. These data indicate abundant (**Fig. T22B**, red and green dots), large (**Fig. T22A**, red and green dots) particles nearshore and off the Pt. Conception region of upwelling. The increasing abundance of large particles nearshore in spring may be due to both large zooplankton (e.g. *Calanus pacificus*) and organic aggregates, formed from phytoplankton, in regions of high productivity. Further data analysis is being performed to infer the relative contributions of fragile particles as well as zooplankton types, particularly larger copepods.
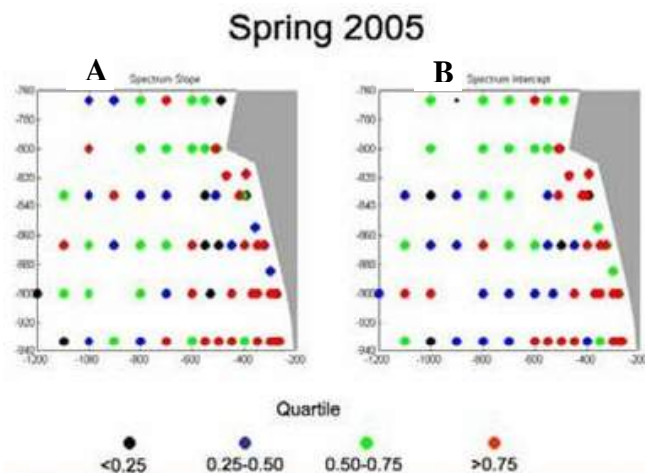
Fig. T22. Spatial pattern of LOPC-derived (**A**) size spectrum slopes and (**B**) size spectrum intercepts, for the Spring 2005 cruise. Data are expressed as quartiles representing the lower 25 %tile, 25-50 %tile, 50-75 %tile, and upper 75 %tile of slopes and intercepts,

Spawning of small pelagic fishes in the CC System

The eggs of small pelagic fishes – sardines, anchovy, jack mackerel – are collected on CalCOFI-CCE cruises while transiting from station to station using the Continuous Underway Fish Egg Sampler (CUFES, developed by Dave Checkely). Since the late 1990's springtime CUFES sampling has covered the area between San Diego and Monterey or San Francisco. Analyses by Ralf Goericke show that average egg densities show large variability over the last 9 years, with sardine egg densities possibly declining and anchovy egg densities possibly increasing.

In addition, geographical centers of spawning activity calculated from the egg distributions observed during the annual spring cruises show that centers of spawning activity for the 3 species are well separated in space (**Fig. T23**, red line, blunt arrow). Notable in the time series is a dramatic shift in the spawning center for sardines in 2006. This is possibly related to the emergence of southern and northern populations of sardines over the last decade.
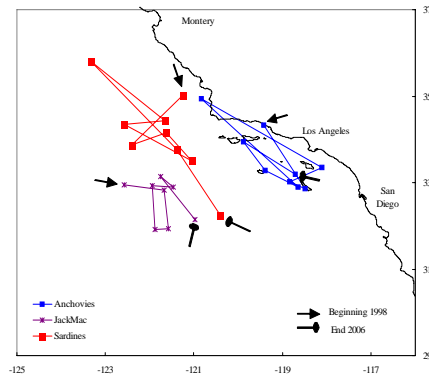
Fig T23. Egg densities were averaged over the CUFES survey area and centers of spawning activity were calculated for each year from egg densities at the 99 stations. Shown are shifts in these centers over time for anchovies (blue), sardines (red), and jack mackerel (black). The beginning of each time series (1998) is indicated with a sharp-tipped arrow and the end of the time series (2006) with a blunt-tipped arrow.

The spawning of small pelagic fish is often thought to be affected by temperature and salinity; i.e. the fish actively choose habitats in Temp-Salinity space that are optimal. If true, one would expect the average T or S where spawning occurs to be independent of environmental T or S (in our case the average SST for the 99 stations covered in the analysis). Plots of spawning T or S vs. environmental T or S (**Fig. T24**) show these to be significantly related in many cases. The high co-variation of T and S data suggests that the selection of spawning areas does not solely occur based on the physical properties of the environment.
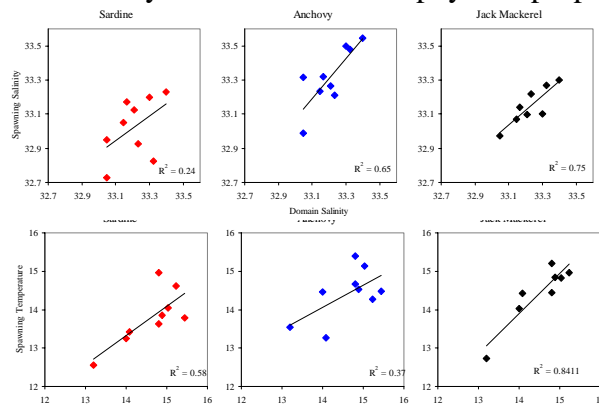
Fig T24. Top Panel: The egg-density-normalized temperatures for the spawning areas of Sardine (red), Anchovy (blue) and Jack Mackerel (black) are plotted against the average temperatures of the CUEFS survey area for the years 1998 to 2006. **Bottom Panel**: The egg-density-normalized salinities for the spawning areas of Sardine, Anchovy and Jack Mackerel are plotted against the average salinities of the CUEFS survey area for the years 1998 to 2006. The r^2 for regressions of the two variables are given.

30

Spray ocean glider resolution of ecosystem variations

As a complement to other ocean measurements made in the CCE LTER site, *Spray* ocean gliders are now regularly sampling CalCOFI lines 80 and 90 (**Fig. T25**). Quarterly

Fig. T25. *Spray* ocean gliders along lines 80 and 90.

shipboard sampling is too infrequent to resolve some key processes in the CCE LTER site, such as the onset and decay of El Nino. Remote sensing is extremely useful but does not resolve subsurface structure. To improve our ability to resolve ecosystem transitions, Mark Ohman and Russ Davis have developed an ecosystem

observation program using *Spray* ocean gliders, designed and built in Davis' Instrument Development Group at Scripps. This program is supported by the Moore Foundation and is of direct benefit to the CCE LTER site. The completely autonomous *Spray* gliders have bidirectional communications via the Iridium satellite network, permitting adaptive sampling and remote navigation across coastal and open ocean environments. Data from vertical profiles to a depth of 500m are telemetered ashore and posted on a publicly accessible website immediately upon completion of each dive. At present our sensors include a pumped CTD, chlorophyll *a* fluorometer, and 750 kHz SonTek Acoustic Doppler Profiler for zooplankton acoustic backscatter and velocity shear. With this particular payload the gliders have an endurance of approximately 100 days, at which time we remotely navigate them close to shore and recover them from a small vessel.

In October, 2005 we initiated a measurement program with *Spray* and immediately uncovered a persistent anticyclonic eddy off Pt. Conception (**Fig. T26**, left). The phytoplankton Chl*a* field and, to some extent zooplankton acoustic backscatter, change markedly at both the inshore and offshore frontal boundaries associated with this eddy (**Fig. T26,** right). Such features are important sources of biophysical structure in this ecosystem. Our process cruise experiments are now carefully situated in relation to the mesoscale features defined by real-time glider sections.
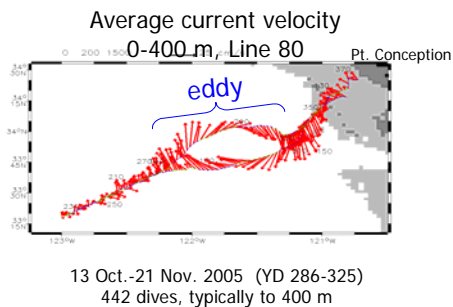
Fig. T26. (left) Average current velocity (0-400 m) and (right) Vertical sections of density, Chl*a* flourescence, and Acoustic Backscatter, in Oct. 2005. The coast is on the right, offshore to the left. Note the well-defined fronts (dotted red lines) at the inshore and offshore boundaries of the eddy.
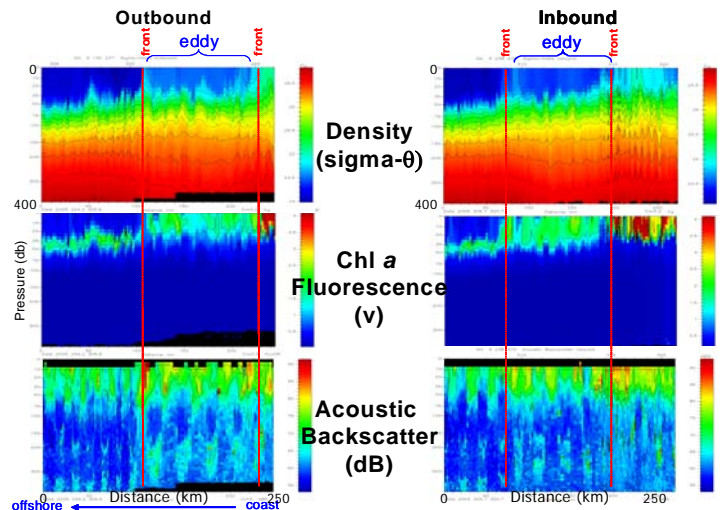
The Dana Point Ocean Institute (OI) coastal time series

The CCE-LTER program has partnered with the Dana Point Ocean Institute not only for the purposes of education and outreach but also to extend our higher frequency observations in the coastal zone. Student cruises that leave from Dana Point multiple times per week are used as a sampling platform. Since the fall of 2005 measurements at a depth of 10 m have been taken at a station ~ 2 km SSE of CalCOFI station 90.028 more than 120 times, involving nearly 1200 students in active scientific research. The variables measures are temperature and concentrations of Chl*a* in two size fractions: total and larger than 3 μm (**Fig. T27**). Recently, these measurements have been complemented with depth profiles of temperature, salinity and fluorescence.
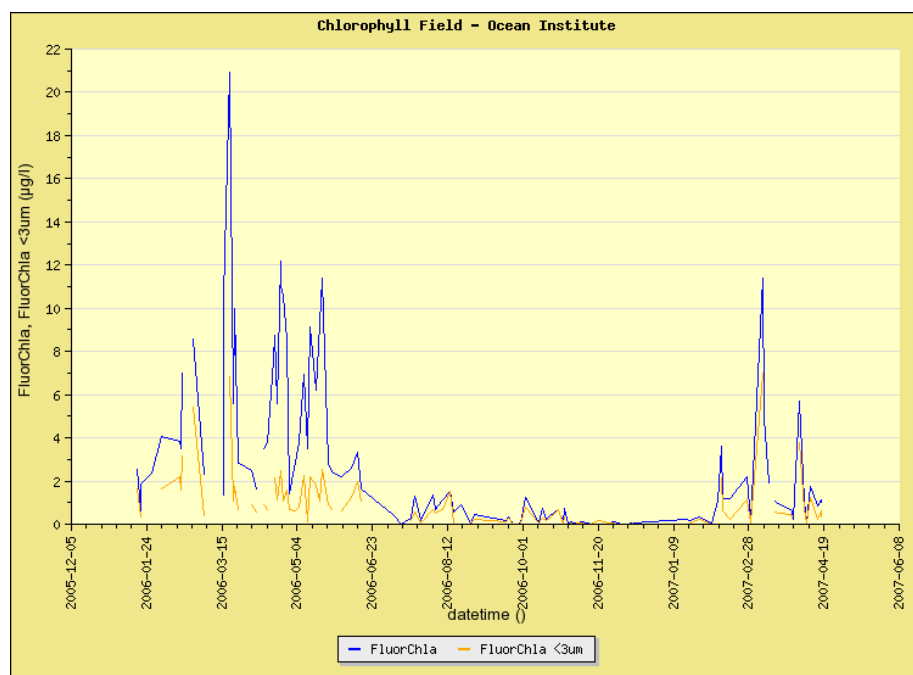
Fig. T27. Time series of Chl *a* off Dana Point. Shown are total concentrations (blue) and concentrations in the < 3 μm size fraction (orange).

Results available so far show the expected pattern of large-size class dominance during the spring bloom and low relative contribution during the low-biomass summer months (**Fig. T27**). These results will be compared to results available from the Scripps Pier and from CalCOFI cruises to determine (1) whether different stations along the coast show a coherent response to season and interannual forcing, (2) whether there are predictable relationships between physical characteristics such as temperature and phytoplankton blooms, and (3) whether changes in community structure with changing total biomass are similar in different nearshore environments.

CCE scientists have supplied collecting equipment (closing water bottles, filtration rack, subsurface probe, Turner Designs fluorometer), supplies (filters, etc.) and, perhaps most importantly, training for OI staff in analytical methods and fluorometer calibration procedures.

MODELING AND SYNTHESIS

These contributions are organized according to our primary hypotheses related to ecosystem changes in the CCS: *in situ changes in stratification and nutrient supply, anomalous advection, and altered predation pressure*.

In situ food web changes in response to altered stratification and nutrient supply

To identify the source of upwelled waters in the CCS, postdoc Ketty Chhak and Emanuel Di Lorenzo (2007, *Geophysical Research Letters* doi:10.1029/2007GL030203) used an adjoint ROMS (ADROMS) model configured for the NE Pacific. Conceptually, the adjoint allows the physical model to be run backwards in time to identify where particular water masses came from. By comparing warm and cool phases of the PDO, Chhak and Di Lorenzo showed striking changes in the source waters and strength of upwelling during PDO oscillations (**Fig. M1**). During the warm phase, upwelled waters near the coast originated from waters above 200 m and transport was dominated by horizontal advection from a large pool to the north of the region. In contrast, upwelling during the cool phase extended below 500 m, with strong vertical advection and mixing. Upwelling during the cool phase thus accesses the deep nutrient pool more efficiently than warm-phase upwelling.
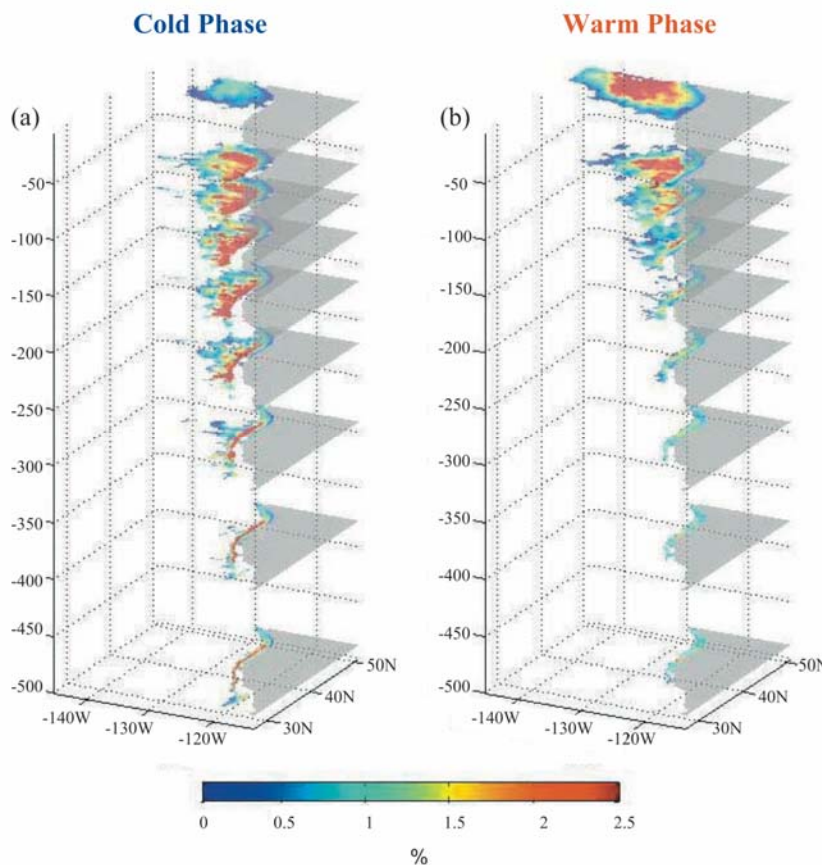
Fig. M1. Sources of upwelled water along the Pacific coast of North America during the cold (left panels) and warm (right panels) phases of the PDO. The color bar indicates the tracer concentration during peak upwelling relative to that one-year prior, showing the origin of the upwelled water. During the warm phase upwelled water comes from shallower depths, and has a strong component of horizontal advection from the north at the surface. Gray area shows the west coast of North America, from just north of Vancouver Island to Baja California. From Chhak and Di Lorenzo (2007).

Upwelled nutrients are the source of much of the biological variability in the CCE. Visitor Dag Aksnes, working with Mark Ohman and French colleague Pascal Rivière. analyzed nutrient and Secchi disk data from the CalCOFI and LTER regions over the past 21 years (2007, *Limnology and Oceanography* 52:1179). They developed an analytical model that related the depth and strength of the nitracline to the downwelling irradiance. This study makes the novel case that irradiance controls nitracline depth. The irradiance, in turn, is affected by the amount of phytoplankton (chlorophyll) in the water, which is ultimately determined by the available nutrients. In this system with multiple feedbacks, the nitracline was found to correlate well with the effect of chlorophyll on the irradiance. The observations were consistent with model predictions, reinforcing the nonlinear nature of the irradiance-chlorophyll-nutrient interactions.

To explore the influence of nutrient supply and grazing on the structure of the CCE, postdoc Heidi Fuchs together with Peter Franks developed a continuum size-structured model of the planktonic ecosystem (submitted ms.). This NPZ model includes allometric scaling of the phytoplankton growth rate, and size-dependence of the prey available to a given size of predator. While the model does not presently have spatial dependence, changing the total amount of nutrient in the model is functionally equivalent to changing the strength of upwelling-driven nutrient flux. Fuchs and Franks found that higher total nutrients (=stronger upwelling) gave ecosystems with shallower size-spectral slopes, a wider range of sizes, and a higher proportion of large plankton (both phytoplankton and zooplankton) (**Fig. M2**). These results were supported by data from grad student Ryan Rykaczewski and David Checkley (submitted ms.), who showed shallower size-spectral slopes during times of strong upwelling in the CCE.
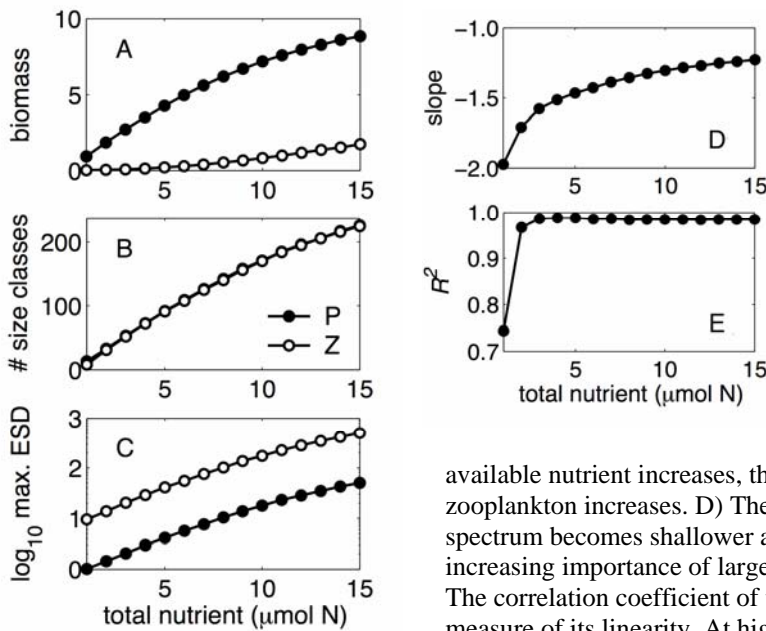
Fig. M2. Changes in planktonic ecosystem structure with the total amount of nutrient available from the Fuchs and Franks continuum size-structured model. A) Total phytoplankton biomass (filled circles) increases monotonically and nonlinearly with total nutrient. Total zooplankton biomass (open circles) increases more slowly. B) The number of size classes of phytoplankton and zooplankton are almost identical, and increase with total nutrient. C) As available nutrient increases, the size of the largest phytoplankton and zooplankton increases. D) The slope of the normalized biomass spectrum becomes shallower as total nutrient increases, indicating the increasing importance of larger organisms at high nutrient levels. E) The correlation coefficient of the normalized biomass spectrum is a measure of its linearity. At higher total nutrient concentrations the spectrum becomes more linear (on a log-log scale), indicating fewer gaps and lumps in the spectra. From Fuchs and Franks (submitted ms.)

Rykaczewski and Checkley (submitted ms.) used models and data to explore the relative importance of coastal wind driven upwelling vs. open ocean wind-stress curl driven upwelling in the CCE. They showed that wind-stress curl, while driving slower upwelling rates, was responsible for the majority of upwelling in the CCE. Furthermore, variations in wind-stress curl driven upwelling over the past 6 decades are correlated with variations in production of the Pacific sardine (*Sardinops sagax*). The coupling of sardine production to upwelling is through nutrient flux-driven changes in the planktonic size structure: sardines feed efficiently on the small plankton generated by slow upwelling.

Grad student Chih-hao Hsieh, working with other students and George Sugihara, published a provocative paper in *Nature* (2005. 435:336) contrasting the temporal dynamics of physical and biological time series in the ocean, with emphasis on data originating from CalCOFI and our LTER site. While the physical ocean and atmosphere time series consistently showed linear dynamics, the biological time series consistently showed nonlinear characteristics. The significance of this finding is that unexpected biological nonlinearities frequently arise even when the underlying physical environment varies in a linear manner. Consequently nonlinear "regime shifts" cannot be predicted from the physical environment alone. These analyses were extended further in Hsieh and Ohman (2006, *Ecology* 87:1932), which poses a new "Linear Tracking Window" Hypothesis: populations are most likely to track stochastic environmental forcing when their generation time matches the characteristic time scale of the environmental signal (**Fig. M3**). This hypothesis seems to have attracted the interest of other ecologists.
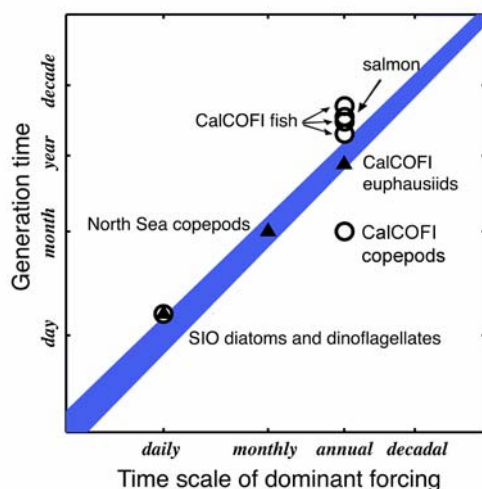
Fig. M3. The Linear Tracking Window Hypothesis (from Hsieh and Ohman. 2006. *Ecology*). Organisms whose generation times match the dominant time scale of environmental forcing fall in the blue "tracking window," and thus show linear population dynamics that track the underlying physical variability (filled symbols). Other organisms whose generation times fall outside the blue tracking window show nonlinear dynamics (open symbols).

Thus, with respect to the hypothesis of ***In situ* food web changes in response to altered stratification and nutrient supply,** the CCE LTER modeling group has identified decadal-scale changes in the structure of wind-driven upwelling, quantified how these changes affect the size structure of the planktonic ecosystem, and showed that these changes in size structure explain much of the decadal variability in sardine production in the region.

Altered predation pressure

The continuum size-structured model of Fuchs and Franks (submitted ms.) is an ideal vehicle to explore the importance of grazing preference on the structure and dynamics of the planktonic ecosystem. Fuchs and Franks ran simulations using two different grazing functions: one represented specialist predators that ate only a narrow size range of prey, while the other represented generalist predators. Model ecosystems with generalist predators (e.g. salps, doliolids) had higher biomass, lower diversity, fewer top predators, and steeper and gappier size distributions than ecosystems with specialist predators, consistent with data from the CCE. The relative abundances of generalist and specialist planktonic predators are strongly influenced by ocean temperature, suggesting that climate-driven shifts in predator assemblages will affect community feeding preferences and may dramatically alter plankton size distributions and productivity.

Sustained, anomalous alongshore advection of different assemblages

Di Lorenzo et al. (submitted ms.) used the Regional Ocean Modeling System (ROMS) forced by surface wind stress and heat fluxes to simulate the NE Pacific during the period 1950-2005. The model accurately reproduced decadal fluctuations in SST that are the central elements of the PDO. It has been noted for some time, however, that fluctuations in the PDO do not explain the variability of salinity or nutrients in the CCE. Di Lorenzo et al. identified a second mode of variability in the model, which they termed the North Pacific Gyre Oscillation (NPGO). This mode, independent of the PDO, was highly correlated with fluctuations in
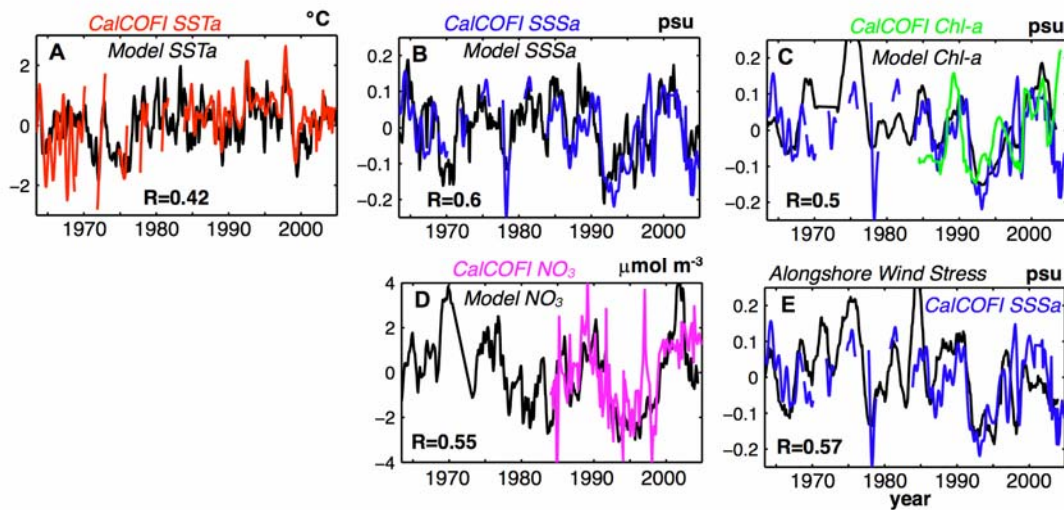
Fig. M4. Comparison of CalCOFI-LTER observations and model time series (ROMS) spatially averaged over the Southern California Current. Units are at the top right corner of each panel. A) CalCOFI sea surface temperature anomalies (SSTa, red) and model hindcast (black). The correlation is significant at the 96% level. B) CalCOFI sea surface salinity anomalies (SSSa, blue) and model hindcast (black). Correlation is significant at the 99% level. C) CalCOFI surface Chlorophyll a anomalies (Chl-a, green) and model hindcast (black). Correlation is significant at the 80% level. The Chl-a anomaly time series has been smoothed with a 2 yr running average and standardized to units of psu to compare with the CalCOFI SSSa (blue, same as panel B). D) CalCOFI nitrate anomalies (NO3a, magenta) at 150 m depth, and model hindcast (black). Correlation is significant at the 99% level. E) CalCOFI SSSa and low-frequency (2 year running mean) alongshore wind stress anomalies. Correlation is significant at the 98% level. From Di Lorenzo et al. (submitted ms.)

salinity and nutrients through changes in large-scale horizontal advection of freshwater from the north (**Fig. M4**). A simple ecosystem model coupled to the physical model showed that fluctuations of chlorophyll in the CCE were highly correlated with the NPGO (not the PDO), providing a novel and powerful explanation for physical forcing of ecosystem changes in the CCE.

Data Assimilative Model Forecast

For the first time, we used a ROMS numerical ocean model forecast to plan experimental activities on a process cruise. In April 2006, immediately prior to our first experimental process cruise (P0605, in May 2006), a CalCOFI/LTER time series cruise completed a 2-week survey in our region. The hydrographic data from that cruise were quickly passed to the ROMS modeling team (Emanuel DiLorenzo, Art Miller, and others), who assimilated the data and ran a 30-day forecast using the climatological wind field. This forecast, which we examined while steaming toward our study site in the form of an animated movie illustrating temporal changes of Sea Surface Heights and Temperature, projected an intensification of upwelling in the vicinity of Pt. Conception over the course of the process cruise. This forecast was used to site our first experimental Lagrangian drift station in a water parcel experiencing an early phase of upwelling. The model forecast proved to be correct.

INFORMATION MANAGEMENT

The CCE information management plan is in its third year, having adopted an informatics team-building approach that now includes programmers, data analysts, system administrators, undergraduate students, volunteers as well as science studies graduate researchers, graduate students, and CCE research participants in general. Further, Ocean Informatics (OI) has been developed as a conceptual framework for cross-project work carried out in collaboration with data management associates. Related projects include the Palmer Station LTER (PAL), the California Cooperative Oceanic Fisheries Investigations at Scripps Institution of Oceanography (CalCOFI-SIO) and the Southwest Fisheries Science Center (CalCOFI-SWFSC). OI focuses on data and information systems, informatics and information infrastructure in addition to collaborative design practices and participatory design activities (see **Fig. I1**).

Work on the CCE LTER technical infrastructure led to purchase of a server with coordinated storage that could be incorporated into an expanded division computational infrastructure. In 2006 a second server was purchased in order to expand LTER storage to the terabyte level and to isolate functionality of web services from user and file services. File sharing and LDAP authentication were launched for the CCE community in 2005 and 2006, respectively. In 2007, arrangements for a computational recharge facility were supported as a growth strategy central to cross-project infrastructure and resource sharing.

The CCE web site was launched in 2005 with personnel and activity lists. We added bibliographic and media gallery modules in 2006. Cruise web pages have been developed for the process cruises. Each site includes a dynamic cruise mapper, an activity glossary, a sampling grid calculator, and access to static data files. A shipboard eventlogger was designed to facilitate data flow from field to the community information system. The logger creates an authoritative list of shipboard activities and is a key metadata device for subsequently interelating diverse datasets. This file is among the first to be posted to the cruise web sites.

Fig. I1, illustrating selected LTER CCE IM accomplishments: eventlogger implementation, computational infrastructure building, Ocean Informatics team development, and the Datazoo information system as a multi-project publishing forum and the site web page as a community hub.

Our information system, called Datazoo 2.0, is a central repository for data and metadata of CCE LTER and associated member projects (see **Fig. I2**). It provides data aggregation, ingestion, description, visualization, download, integration, and standardized exchange. New web service features include metadata forms and dataset submission templates; these represent mechanisms for changing data practices and avoiding traditional data

bottlenecks where only experts are able to interact with a data/information system. New conceptual approaches include a time-series approach to dataset collection storage and metadata granularity using semantic suggestion for development of controlled vocabulary. Datazoo is coded primarily in PHP, using an object-oriented design focusing on code reusability. Classes are defined for logical entities. These classes provide an abstract interface into the MySQL database backend, and support query, update, insert, and delete operations. All interaction with Datazoo is through web pages laid out in HTML and styled with CSS. Javascript is used on many pages to create more dynamic, user-friendly interactions. Browse, query, and edit interfaces allow multiple users to interface with the system. As with the backend code, interface design has focused on generic, reusable elements so that, for instance, a module needing to provide user edit capabilities will make use of the Datazoo edit code. Initial work with datasets stimulated development of a set of tools to help with file formatting. These tools provide users with the ability to create a time column in a standardized format using a date-time calculator, to determine station locations from latitude and longitude in a single or batch upload mode using a grid calculator, and the ability to add columns to individual datasets from an eventlog using a log tool. Launch of the Datazoo system has been planned for September 2007 with data population having begun mid summer.
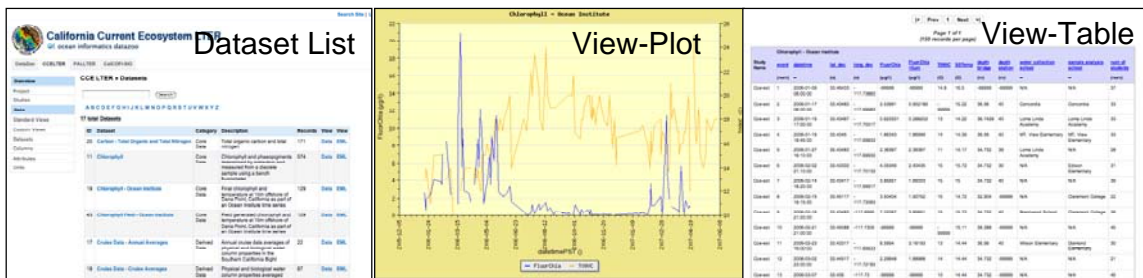
Fig. I2, illustrating the CCE LTER Datazoo Information System list of datasets and viewing options in the form of tables and plots.

The Ocean Informatics team led an LTER Network Unit Repository Working Group, designing code and populating a unit registry. This module was demonstrated at the LTER IM Committee meeting in 2005 and the code made available through an LTER Network code library. Subsequently, we downloaded and installed the code at our site. It provided the basis from which an attribute dictionary was designed and developed and was followed by an attribute qualifier dictionary that allows data to be described to the column level. This represents an Ocean Informatics augmentation of the EML standard; it was described and demonstrated at the 2007 LTER IM committee meeting. Datazoo web interfaces were developed for editing metadata at the study, dataset, attribute and unit levels. Datazoo generates metadata that meets the EML standard; CCE recently published its first dataset to Metacat. Future plans include development of generic QA/QC tools such as an Event Log Validator to detect duplicate event numbers and vagrant latitude or longitude entries. There is an ongoing effort with development of controlled vocabularies and exploration of incorporation of a thesaurus in collaboration with community partners.

Ocean Informatics is created as a learning environment where informatics professionals have an opportunity to augment their technical skills and conceptual understanding. A recent move to new laboratory space was taken as an opportunity to create a Design Studio,

39

underscoring the notion of a new type of design environment. Datazoo pre-launch activities have included a focus on community engagement through demos and system adjustments. In addition, documentation has begun with a system overview and a series of guidelines that are online as a first step toward a more extensive documentation effort.

From the outset, science studies participants have been collaborators, first as participant observers and more recently as action researchers. This unique interdisciplinary collaboration has been central to development of new approaches and data practices, enabling transformation of a data/information management component to an informatics team able to design and develop robust local information infrastructure needed to support collaborative science in a sustainable manner. Informatics activities and events are summarized in event flyers as well as the LTER Databits Newsletter and Journal articles. The focus on a learning environment provides the training, inspiration, and collaborative experiences that contribute to productivity, engagement, and stability of an informatics team within a university research setting.

CCE LTER Web Links:
Home webpage: http://cce.lternet.edu/
Cruise webpages: http://cce.lternet.edu/data/cruises/
CCE Information system home page: http://cce.lternet.edu/datazoo
Datazoo multi-project information system: http://oceaninformatics.ucsd.edu/datazoo
Databits IM articles: http://cce.lternet.edu/publications/documents/LTER_databits.php
LTER Network Unit Repository prototype: http://fire.lternet.edu/customUnit/

EDUCATION AND PUBLIC OUTREACH

The success of the California Current Ecosystem LTER Education and Public Outreach program (CCE EPO) depends, in part, on the participation and contributions of members across the site team (**Fig. E1**). We have drawn upon the remarkable group of research scientists, graduate students, information managers, programmer analysts, educators, students, and volunteers to build the outreach

Fig. E1. CCE LTER group photo. Jan. 2007

program since its inception in 2004. The role of the Education and Outreach Coordinator is to bridge site research science with education and the broader public. It is a liaison role that supports the process of translating scientific perspectives and methods, as well as data and knowledge. For CCE, the coordinator (Beth Simmons) has created a bidirectional bridge of communication and interaction with the surrounding community, supported primarily by the S-LTER supplement. These supplemental funds support the education coordinator at 23% time. With this support, Simmons works to maintain successful efforts of education and outreach, but also to innovate and build new elements to CCE's site education programs.

Our K–12 educational efforts at CCE are founded in large part upon the Ocean Literacy Principles (National Geographic, NOAA and other partners, 2005) and the current challenges and opportunities facing the nation and the U.S. west coast in both formal and informal education arenas. Our participation in the California Regional Conference on Ocean Literacy (2006) has guided our efforts in creating a K-12 education and outreach program that centers around educating the public to make informed decisions about the ocean and its resources. We have participated in several Ocean Literacy Network collaborations utilizing these principles to help translate CCE site science concepts. This alignment with externally defined principles ensures that our educational products parallel state and national education standards, which is particularly important since the State of California is currently poised to lead the nation in integrating environmental science practices into primary and secondary schools (Schoedinger et al. 2006). In the local San Diego community, the CCE EPO program has developed a relationship with the University of California, San Diego Preuss School (a minority-serving charter school) and the Rancho Bernardo Public High School to disseminate information, engage students, evaluate educational materials, and offer professional growth opportunities for educators.

Through participation in professional development initiatives, the outreach program also draws upon the National Science Teachers Association (NSTA), the National Marine Educators Association (NMEA) and the Centers for Ocean Sciences and Education Excellence (COSEE) to keep program development current.

A hallmark of CCE's EPO program is a unique outreach partnership with the Dana Point Ocean

Fig. E2. Ocean Institute staff demonstrate procedures for filtering seawater samples for fluorometric analysis of chlorophyll.

Institute (OI), a nonprofit organization known for its hands-on marine science, environmental education, and maritime history programs. More than 78,000 K-12 students and 6,000 teachers annually participate in the Institute's science immersion programs. Presently, the Ocean Institute has logged 129 distinct sampling events in connection with the CCE site during numerous two-hour cruises. As a result, nearly 1,200 students have actively participated in investigations at sea that form part of their educational experience and also are tied to CCE site science. The focus of this effort has been development of a time series of phytoplankton biomass (as

chlorophyll *a* in two size fractions) in relation to variations in ocean temperature in the ocean off Dana Point (**Figs. E2 and E3**). The purpose is to convey a few key concepts: (1) variations in phytoplankton biomass and ocean physical properties are often interrelated, (2) different size fractions of phytoplankton (picoplankton < 3 μm and larger phytoplankton) show different levels of variability over time, and (3) pelagic food web structure may differ depending on the dominance of different size classes of phytoplankton at the base of the food web.   The data resulting from the Ocean Institute CCE time series thus contribute both to their educational mission and to CCE investigations of coastal ocean

processes. This project is featured on our outreach web page to highlight both the OI partnership and the chlorophyll/temperature time series results. We are developing some of the OI time series data into curriculum modules accessible by educators and the general public via the world-wide web. Eventually these data will be linked to data from the Scripps pier chlorophyll and temperature time series, in order to demonstrate the extent of coherence of near-shore variations in plankton properties at different locations along the California coast to students and the general public.

Fig. E3. Middle school students aboard the R/V *Sea Explorer* participate in the chlorophyll/temperature time series project.

We are also a developing a children's book series project through the LTER Schoolyard program. Our book proposes to link two pelagic oceanic ecosystems: a coastal upwelling biome in the southern sector of the California Current (CCE) and a polar ice-influenced environment west of the Antarctic peninsula (PAL). This cross site project with Palmer Station LTER, examines the most abundant species of krill in the respective ecosystems, *Euphausia pacifica* and *Euphausia superba,* and the contrasting life histories and challenges they face. The exploration of the predators and prey with which the two species of krill interact, their life history adaptations, and the contrasting ocean environments of a temperate and polar ocean ecosystem holds inherent fascination for young readers and provides an excellent teaching platform. We are fortunate to have children's book author Mary Cerullo, writer of over a dozen childrens' books, to assist with the text of the book.   Professional photographer Bill Curtsinger, with over thirty-three articles featured in National Geographic, will complement the basis of our children's book with his award-winning photography (see **Fig. E4**). A supplemental curriculum guide is being developed to broaden the marketability of the book bringing it into the educational sector. We are meeting the demands of a fall

Fig. E4. Education and Outreach Coordinator Beth Simmons, photographer Bill Curtsinger and children's book author Mary Cerullo at NMEA conference, Maine, 2007.

publishing schedule beginning with the receipt of manuscript, photography and art by January 1st, 2008.

In addition to the elementary school arena, local high school students and numerous undergraduates have worked in several CCE scientists' laboratories. Two UCSD undergraduate courses that draw directly on CCE site faculty and research results have recently been added to the undergraduate curriculum. A REU program was initiated in summer 2007 with two excellent students. At the graduate level, two seminars have been taught at SIO addressing LTER-based ecosystem research and CCE site-based science, respectively. 19 U.S. graduate students and 2 other visiting international students have participated in CCE cruises and related modeling studies, in addition to 6 postdocs. In the coming year, our ongoing relationships plus new discussions with San Francisco's Exploratorium may offer additional opportunities to foster new education-research ties. Some of the primary CCE EPO partners are listed below.

Education and Outreach Partners
Aquarium of the Pacific - Interactions with the aquarium in Long Beach, CA for education.
Aquatic Adventures - Project 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 program-UC math and science summer school enrichment program, grades 8-12.

References:

1.   Schoedinger, Sarah et al. (2006) Ocean Literacy through Science Standards, COSEE workshop report http://coexploration.org/oceanliteracy/documents/workshopreport.pdf.
2.   Ocean Literacy: Essential Principals and Fundamental Concepts, workshop report (2005) http://www.coexploration.org/oceanliteracy/documents/OceanLitChart.pdf.
3.   Ocean Literacy Network: http://www.coexploration.org/oceanliteracy/.

SITE MANAGEMENT

EXCO

The CCE site has an Executive Committee (EXCO) consisting of a representative from each of the major elements of the CCE program

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CCE EXCO Membership

Program Element	Representative
Project Direction	Mark Ohman
Time Series Studies	Ralf Goericke
Process Cruises	Mike Landry
Modeling	Peter Franks
Information Management	Karen Baker

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Each of the EXCO members also has financial management responsibilities for the corresponding part of the CCE budget. Each is charged with monitoring and approving expenditures, evaluating progress, and assessing unanticipated needs.

The EXCO reviews overall scientific progress, financial issues, and planning on behalf of the site every 1-3 months.

Program Office Coordinator

One year ago, Ms. Robin Westlake Storey was hired as a 50% time CCE Program Office Coordinator to manage the CCE office (located in room 2147 Sverdrup Hall, 858-534-1547). She serves as a liason among scientists, graduate students, technicians, the education and outreach coordinator, the LTER Network Office, and others. She helps prepare annual reports to NSF, annual supplement proposals, maintains publication lists, coordinates meetings, and helps with some aspects of process cruise preparations.   Robin has a MSc degree in Biology and has published six peer-reviewed scientific papers in molecular genetics and photogrammetric censusing of marine mammals.

PI's

We have two levels of PI involvement in the CCE site, co-PI and Associate. Co-PI's tend to have more of their research program focused in the CCE site and more direct involvement in project planning, proposal development, etc. Associates maintain active scientific interest in CCE goals and research. People can move from one level to another, and new people can participate (2 new Associates have been added since our site was initiated).

Graduate Student Representative

Our new graduate student rep is Ryan Rykaczewski (Biological Oceanography). Ryan replaces Brian Hopkinson (Marine Chemistry) who is completing his Ph.D next month.after about 1-1/2 years of service to CCE. Brian (and other students) represented CCE at the LTER student symposium in Oregon last year, at the ASM, and in local CCE meetings.

REU Coordinators
Kathy Barbeau, assisted by Lihini Aluwihare and Mike Landry, are the faculty members who administer our REU program. Our first 2 REU students just completed their research this summer (2007).

Annual site meetings
We have annual site meetings, to which all PI's, Associates, graduate students, postdocs, and key technical people are invited. Often visitors are invited as well. The first annual site meeting was held at SIO in Dec. 2005 and the second in Jan. 2007. We anticipate the next meeting to be in winter 2008. These meetings are used as a forum to review progress, increase dialogue within program elements, and foster exchange across the program. Graduate students are particularly encouraged to participate. At the annual meetings we also openly discuss program priorities for Supplemental requests.

Process cruise meetings
Prior to each experimental Process Cruise, we have open meetings to discuss science objectives, logistical issues, and cruise plans. Following the process cruises, we have follow up meetings to exchange preliminary results and increase dialogue among cruise participants, modelers, and others.

CCE LTER News
The lead PI (or Program Office Coordinator) distributes news within the CCE community by an email newsletter entitled "CCE LTER News." This is separate from one-off emails on specific topics and serves to keep people who are inside or outside La Jolla informed about recent developments, forthcoming and past meetings, annual supplement opportunities, national LTER network events, etc.

APPENDIX I.   Personnel involved in the CCE site
Table 1. PI's participating in the CCE LTER site.

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 and Function
Art Miller	Co-PI	SIO	Physical Oceanography; Modeling
Greg Mitchell	Co-PI	SIO	Remote Sensing and Bio-optics
George Sugihara	Co-PI	SIO	Nonlinear Modeling
Farooq Azam	Associate	SIO	Bacteria/Microbial Food Webs
Steven Bograd	Associate	PFEL	Physical Oceanography
Ron Burton	Associate	SIO	Molecular Probes for Protists
Dan Cayan	Associate	SIO	Atmospheric Physics
Teresa Chereskin	Associate	SIO	ADCP Currents
Emanuel DiLorenzo	Associate	Georgia T.	Biophysical Modeling
Russ Davis	Associate	SIO	Physical Oceanography
David Hyrenbach	Associate	Duke	Seabird Ecology
Brian Palenik	Associate	SIO	Microbial Diversity
Dan Rudnick	Associate	SIO	Mesoscale Ocean Physics
Tony Koslow	Associate	SIO	Planktivorous Fishes
Beth Simmons	E&O Coord.	SIO	Education and Outreach
Ken Smith	Associate	MBARI	Deep-sea Benthic Ecology
Bill Sydeman	Associate	PRBO	Seabird Ecology; Marine Mammals
Elizabeth Venrick	Associate	SIO	Phytoplankton Floristics

Visiting PI's

Aksnes, Dag	Visitor	Bergen	Optical oceanography/modeling
Chekalyuk, Alex	Visitor	Lamont	Hyperspectral methods
Rivière, Pascal	Visitor	Brest	Bio-physical modeling

Other

Cerullo, Mary	Author	independent	Children's book author
Westlake Storey, Robin	Coordinator	SIO	CCE Program Office Coordinator

SIO= Scripps Institution of Oceanography, PFEL=Pacific Fisheries Environmental Laboratory, Georgia T=Georgia Institute of Technology, Duke = Duke University, MBARI=Monterey Bay Aquarium Research Institute, PRBO = Pt. Reyes Bird Observatory Conservation Science, Bergen = University of Bergen (Norway), Lamont = Lamont Doherty Earth Observatory, Brest = Université de Brest Occidentale (France)

Table 2. **Postdoctoral investigators and graduate students participating in the CCE LTER site.**

Postdoctoral Investigators

Name	Lab Affiliation	Institution	Interests
Fuchs, Heidi	Franks	SIO	Biophysical modeling
Buck, Kristen	Barbeau	SIO	Trace metal geochemistry
Chhak, Ketty	DiLorenzo	Georgia T.	Biophysical modeling
Li, Qian	Franks	SIO	Biophysical modeling
Ward, Jessica Raye	Azam	SIO	Microbial ectoenzymes
Wang, Haili	Mitchell	SIO	Bio-optics

Graduate students   * degree awarded

Name	Lab Affiliation	Institution	Interests
Cawood, Alison	Ohman	SIO	Jellyfish
Davison, Pete	Checkley	SIO	Mesopelagic fish
Decima, Moira	Landry	SIO	Euphausiid ecology
DeJesus, Roman	Aluwihare	SIO	DOM
Dupont, Christopher	Palenik	SIO	Cobalt Limitation
Hansman, Roberta	Aluwihare	SIO	DOM
Hanson, Kate	Leichter	SIO	Reef fishes
Hopkinson, Brian	Barbeau	SIO	Iron/light geochemistry
Hsieh, Chih-hao	Sugihara/Ohman	SIO*	Nonlinear modeling
Hull, Pincelli	Ohman	SIO	Evolutionary radiations
Karakoylu, Erdem	Franks	SIO	Copepod behavior
Kim, Hey Jin	Miller	SIO	Modeling
King, Andrew	Barbeau	SIO	Iron geochemistry
Maurer, Ben	Ohman/Jaffe	SIO	Turbulence
Powell, Jesse	Ohman	SIO	Marine snow
Ruhl, Henry	Smith	SIO*	Deep-sea benthic ecology
Rykaczewski, Ryan	Checkley	SIO	Fisheries recruitment
Samo, Ty	Azam	SIO	Marine bacteria
Soldevilla, Melissa	Hildebrand	SIO	Mammal acoustics
Stukel, Michael	Landry	SIO	Particle fluxes
Tanaguchi, Darcy	Landry	SIO	Biophysical Modeling
Vardaro, Michael	Smith	SIO	Deep-sea benthic ecology

Visiting graduate students

Name	Lab Affiliation	Institution	Interests
Romagnan,Jean-Baptiste	Ohman	Paris*	Zooscan analyses
LeBlond, Julien	Barbeau	Aix-Marseille	Trace metal geochemistry
Linacre, Lorena	Landry	CICESE	Microzooplankton grazing
Stewart, Neil	Aluwihare	Capetown	DOM
Yoshinaga, Marcos	Aluwihare	Sao Paulo	DOM

Graduate students collaborating abroad

Name	Lab Affiliation	Institution	Interests
Perruche, Coralie	Rivière	Brest	Biophysical Modeling
Raimonet, Melanie	Rivière	Brest	Biophysical Modeling

SIO= Scripps Inst. of Oceanography, Paris = University of Paris, 6; CICESE = Centro de Investigacion Superior de Ensenada, Mexico; Aix-Marseille = University of Aix-Marseille, France; Capetown = University of Capetown, South Africa; Sao Paulo = University of Sao Paulo, Brazil; Brest = Université de Brest Occidentale, France

Table 3. **Technical personnel, undergraduate students, and cruise volunteers participating in the CCE LTER site.**

Technical Personnel

Name	Institution	Position
Chong, Laurie	SIO	Staff Research Associate
Dovel, Shonna	SIO	Staff Research Associate
Eaton, Josh	WHOI	VPR technician
Haber,Shaun	SIO	Web and database programming
Kahru, Mati	SIO	Project Scientist/ Remote Sensing
Kortz, Mason	SIO	Web and database programming
Reynolds, Susan	SIO	Staff Research Associate
Roadman, Megan	SIO	Staff Research Associate
Seegers, Brian	SIO	Staff Research Associate
Taylor, Andrew	SIO	Staff Research Associate
Townsend, Annie	SIO	Senior Museum Scientist
Wanetick, Jerome	SIO	Computational Center Director
Ward, Nick	SIO	Web and database programming
Yarmey, Lynn	SIO	Programmer/Analyst

Undergraduate Students

Name	Lab Affiliation	Institution	Interests
Tsyrklevich, Kate	Ohman	**REU**- UCSD	Mesozooplankton grazing
Bundy, Randelle	Barbeau	**REU**- UCSD	Trace metal geochemistry

(Apart from the REU program, several other undergraduates have participated in different labs)

Cruise Volunteers

Name	Home state	Name	Home state
Aubery, Sara	California	Kelly, Rachel	Oregon
Balch, Debbie	California	Lee, Dong-Yoon	[South Korea]
Davis, Edward	Tennessee	Lewis, Jeffrey	Oregon
Erez, Oya	New York	Liddell, Kenneth	California
Feakins, Jonathan	Illinois	Seegers, Bridget	California
Feldman, Lindsey	Massachusetts	Sheffield, Lisa	California
Fitzpatrick, Dylan	California	Spear, Natalie	California
Jensen, Dave	Oregon	Vollmer, Beth	Ohio
Hofheimer, Jean Lea	Massachusetts		
Kansteiner, Matt	California		

Table 4. **Organizational Partners**

International
CICESE, Ensenada, Mexico - Studies of microzooplankton grazing in Pacific coastal waters, and mesozooplankton sentimental species.

TWISTED - Collaborative work with French research modelers, members of 'ToWard Integration of Subgrid Turbulence in Ecosystem Dynamics.'

University of Aix-Marseille, France - Collaborations with the Barbeau lab on trace metal studies.

University of Bergen, Norway - Collaborative research concerning long-term changes in optical properties of the CCE region

Université de Brest Occidentale, France - Collaborations in physical-biological modeling
University of Paris and Villefranche-sur-mer, France- Collaborations on zooplankton image analysis.

University of Tokyo; National Research Institute of Fisheries Science; Nagoya University; JAMSTEC; Hokkaido University, Japan - International Workshop on collaborative studies for ecosystem variation and climate change in the North Pacific

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U.S.A.
Cascadia Research - Marine mammal studies

Duke University and University of Washington - Studies of marine birds

Georgia Institute of Technology - Cooperative modeling project.

Lamont-Doherty Earth Observatory of Columbia University and **NASA Goddard Institute for Space Studies** – Phytoplankton optical properties using hyperspectral methods (ALF)

Monterey Bay Aquarium Research Institute - Collaborative research concerning deep-sea benthic ecology

NOAA Pacific Fisheries Environmental Lab - Analysis and publication of hydrographic data.

NOAA/Southwest Fisheries Science Center - Collaborative efforts with scientists and seagoing personnel

Point Reyes Bird Observatory Conservation Science- Studies of marine birds

San Diego Supercomputer Center - Staff assisting with Information Management design.

Woods Hole Oceanographic Institution - Logistical and technician support on research cruises

CCE LTER Team
First Annual Meeting, Scripps,
Dec. 2005

CCE LTER Team
Second Annual
Meeting, Scripps,
Jan 2007

CCE Process Cruise P0704 Team
at sea on the R/V *T.G. Thompson*
April 2007

CCE LTER Station Plan