

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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TITLE OF PROPOSED PROJECT LTER: Nonlinear transitions in the California Current Coastal Pelagic Ecosystem						
REQUESTED AMOUNT \$ 4,860,000	PROPOSED DURATION (1-60 MONTHS) 72 months		REQUESTED STARTING DATE 09/01/04		SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE	
CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW						
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CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Appendix C of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency?

Yes

No

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Appendix D of the Grant Proposal Guide.

Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding \$100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding \$150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

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(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than \$10,000 and not more than \$100,000 for each such failure.

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Project Summary

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.**

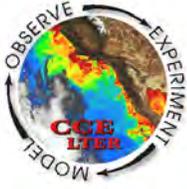
Broader Impacts: We will have state of the art **Information and Data Management**, to serve data and metadata internally, to other LTER partners, educators, the general public, and policy makers. An active **Education and Outreach** program will team scientists with CA COSEE and 3 external partners 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.

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



Nonlinear Transitions in the California Current Coastal Pelagic Ecosystem

This proposal presents a plan to develop an LTER site for the California Current pelagic Ecosystem (CCE). This new site will build on what has been learned from the unparalleled suite of coastal observations developed by CalCOFI (the *California Cooperative Oceanic Fisheries Investigations*) since its inception in 1949, but move far beyond that program. The new site will focus specifically on the *mechanisms* leading to transitions between ecosystem states. The proposed research program is coordinated with three interwoven components: **Experimental Process Studies** focused on hypothesized mechanisms leading to system transitions; space-resolving **Time Series** that explore alternate hypotheses through characterization of ecosystem responses on time scales from hours to decades; and integrated **Modeling** studies that synthesize experimental and observational results, provide a platform for hypothesis-testing and eventually ecosystem forecasting, and help to optimize the sampling program.

The California Current System (CCS) is a **coastal upwelling biome**, as found along the eastern margins of all major ocean basins. These are among the most productive coastal ecosystems in the world ocean. The CCS sustains active fisheries for a variety of finfish and marine invertebrates, modulates weather patterns and the hydrologic cycle of much of the western United States, and plays a vital role in the economy of myriad coastal communities. To set the context for this proposal, we will illustrate below the importance of El Niño, Pacific Decadal Oscillation, and a Secular Warming Trend in altering the structure and dynamics of the CCE, leading to the following central questions: *What are the mechanisms leading to different ecosystem states in a coastal pelagic ecosystem? What is the interplay between changing ocean climate, community structure and ecosystem dynamics?*

We focus on four principal hypotheses generating changes in this ecosystem:

- **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**

We develop below the research approaches that we will take to address these hypotheses, while concurrently addressing the five core research themes that are held in common across all LTER sites. We anticipate fertile intellectual exchange with colleagues in the LTER program and look forward to expanding our horizons, and those of the existing network, through comparative studies across sites with interests in alternate stable states, El Niño and lower-frequency forcing, and the role of top-down impacts on ecosystem dynamics. A specific long-term goal for this site is to develop a mechanistic, coupled bio-physical model for understanding and forecasting the consequences of high- (e.g., El Niño) and low-frequency climate forcing on pelagic ecosystems of the California Current and similar biomes.

Conceptual Framework

Alternate Stable States vs. Continuum View

Understanding the mechanisms of changes in pelagic ecosystems, not merely describing them, is of vital importance to the management of both living and nonliving resources in the

coastal zone. In the CCS, for example, successful management of commercially important resources (e.g., anchovies and sardines, several species of Pacific salmon, numerous rockfishes and other demersal fishes, market squid, Dungeness crab, abalone, and others) requires knowledge of the causes and consequences of system variability.

Abrupt temporal changes frequently characterize transitions from one regime state to another (e.g., Scheffer et al. 2001), small environmental differences leading to major changes in ecosystem properties. Although the concept of “alternate stable states” has been discussed for many years (e.g., Issacs 1976, May 1977, Knowlton 1992), the NSF Ocean Sciences millennium report recognized the predominance of an “equilibrium” perspective in marine ecology: “*The equilibrium-based theoretical and observational tools that were commonly used in previous decades have poorly equipped the discipline to address the realities of a dynamic and changing ocean environment*” (Brewer & Moore, eds. 2001).

Transitions from one dynamic regime to another can be viewed as changes between identifiable, discrete states. According to this view, ecosystems remain locked into persistence by positive feedback mechanisms until they cross a threshold and are then constrained to a new discrete state (Fig. 1). Such system shifts are often governed by nonlinear processes. On the other hand, given the generally “red” variance spectra (Wunsch 1981) of ocean properties (temperature, Chl *a*, velocity, etc.), long time series, by definition, will always uncover lower frequency forcing. Rather than discrete states, one might therefore expect dynamical variations at a variety of temporal scales, with variations on different scales interacting to give apparent abrupt shifts. It has been pointed out that some of the numerical methods used to identify “regime shifts” can easily generate artifactual step-function transitions (Pierce 2001, Rudnick & Davis 2003).

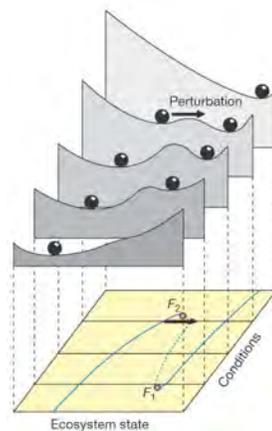


Fig 1. (Upper panel) Stability landscape for a gradient of conditions that modify the basin of attraction, and (Lower panel) the resulting ecosystem state. F_1 and F_2 denote bifurcation points. Scheffer et al. (2001).

If alternate dynamic regimes do exist in the coastal pelagic ocean, identifying them and accurately resolving causal mechanisms is particularly challenging given the underlying “red” variance spectra. Scheffer et al. (2001) identified three criteria for developing the strongest case for the existence of alternative stable states: **(i) observations of repeated ecosystem shifts, (ii) identification of the mechanisms that maintain the different states, and (iii) models that illustrate that these mechanisms can reasonably explain the field observations.** The **California Current Ecosystem LTER Program** will address all three criteria.

Circulation of the California Current System (CCS)

The California Current is the eastern limb of the large, clockwise circulation of the North Pacific Ocean (Fig. 2). As some of the water from the westwind drift turns south and becomes the California Current, it carries cool, fresh water from the subarctic. The California Current *System* off central and southern California consists of the broad, eddy-rich southward flowing California Current (CC), a persistent but variable subsurface California Undercurrent (CUC) centered on the continental slope that carries water of tropical origin poleward, and a circulation over and near the continental shelf that is energetic and highly seasonal, shifting from a wind-driven equatorward flow and coastal upwelling in spring-summer to poleward flow in fall-winter (Hickey, 1979; 1998; Lynn & Simpson, 1987).

Along much of the U.S. west coast, especially during the spring and summer, Ekman transport moves near-surface waters offshore, and cool nutrient-rich water from below is advected into near-shore shallow depths. This wind-driven coastal upwelling is a characteristic feature of eastern boundary currents. Upwelling also occurs offshore of the coastal margin, associated with curl of the wind stress.

The CCS is notable for its vigorous mesoscale variability, with jets that carry upwelled water hundreds of kilometers offshore, sharp fronts and well-defined eddies, particularly during the upwelling season. Kelly (1985) showed that jets are highly variable but tend to recur at coastal promontories. Mooers & Robinson (1984) found that offshore structure depended on interactions with mesoscale eddies. Jets have typical velocities of 30 cm/s, as large as the CC core, with peaks of 80 cm/s (Davis 1985, Kosro & Huyer 1986). Eddy amplitudes (dynamic height anomaly of 0.15 dyn m) can be as large as the total steric height increase across the CC; hence, southward flow of the CCS is often disrupted by strong mesoscale features.

Point Conception, near the northern boundary of our study region, is a coastal promontory associated with strong upwelling and mesoscale variability. The sharply angled coastline has a marked effect on coastal winds (Winant & Dorman 1997), but the CC continues southward, while a series of submarine banks and ridges extend the continental barrier on the inshore side of the current. Inshore, the southward moving mix of subarctic and upwelled waters is mixed with warm-water intrusions from off shore and the south; together these form a counterclockwise circulation pattern, the Southern California eddy. The strength and location of the CC and of the inshore circulation varies seasonally and interannually in response to large-scale changes in ocean/climate patterns. The mix of source waters varies concordantly. The physical and chemical heterogeneity of the CCS south of Pt. Conception makes the region ideal for studying the dynamic responses of pelagic ecosystems to varying conditions.

One particularly attractive feature of the southern CC sector as an LTER site is that it is a biogeographic boundary region for many organisms, both benthic and pelagic. Pt. Conception is located at the boundary between the cool-water Oregonian faunal province to the north and the warmer Californian faunal province to the south (Newman 1979), defined principally from the distribution of benthic marine invertebrates. For zooplankton, Pt. Conception is the approximate mean boundary for many (but not all) taxa, as exemplified by the cool-water, shelf-associated *T. spinifera* and the subtropical *N. simplex* (Fig. 3). **Thus, latitudinal movements of this boundary associated with climate forcing may provide early indications of ecosystem changes to be expected over time elsewhere in the California Current.**

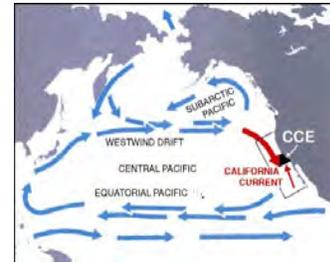


Fig. 2 Schematic illustration of the large-scale circulation of the North Pacific, indicating the location of our LTER site in the coastal CC.

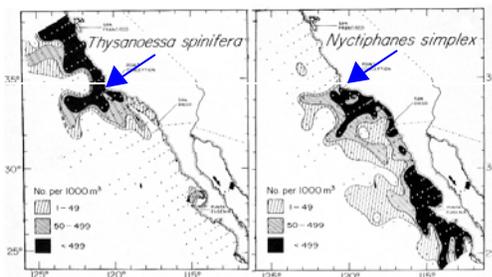


Fig. 3. Geographic distribution of the euphausiids *Thysanoessa spinifera* and *Nyctiphanes simplex* on CalCOFI cruise 7807 (Brinton 1981, as reproduced in Haury et al. 1986). Note Pt. Conception (arrow) as a region of faunal transition, with influences of eddies in the horseshoe-shaped distributions both north and south of this location.

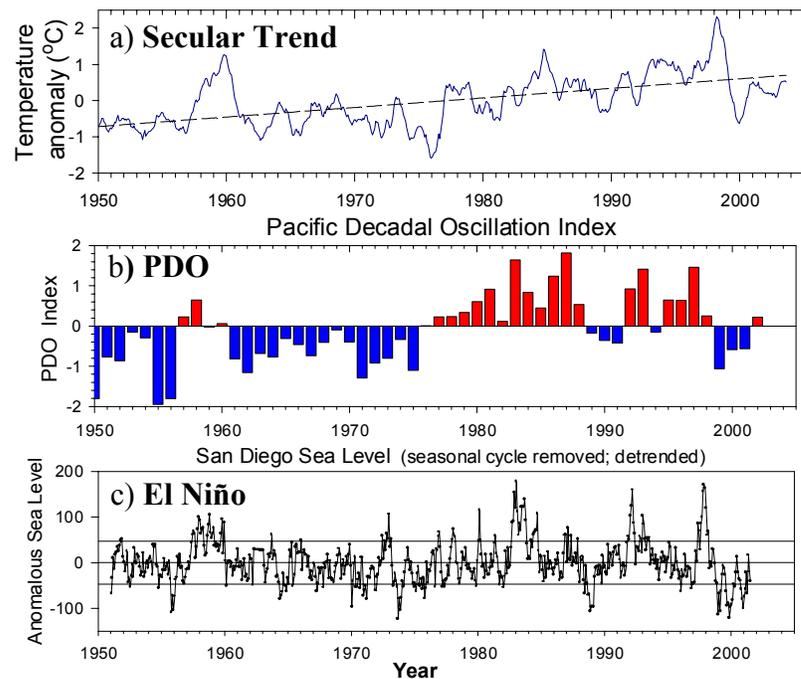
Low-Frequency Physical Forcing and Pelagic Ecosystem Response

Time Scales of Variability: The California Current has been monitored since 1949 by the CalCOFI (*California Cooperative Oceanic Fisheries Investigations*) time series. This Program, initiated following the crash of the California sardine (of Canney Row fame), is now perhaps the most comprehensive physical-chemical-biological oceanographic time series that exists for any coastal ocean. It is a space-resolving time series, which is essential for resolving advective and local effects in a dynamic ocean setting, point sampling being inadequate. Measurements from CalCOFI, Scripps pier (since 1916) and other programs, permit us to characterize some of the dominant low frequency variability in the California Current pelagic ecosystem.

The dominant external forcing on NE Pacific pelagic ecosystems over the past 5 decades includes a multi-decadal **secular warming trend**, as recorded in the Scripps pier temperature record (Fig. 4a), in CalCOFI water column measurements (Roemmich 1992, Roemmich & McGowan 1995a,b) as well as elsewhere in the world ocean (e.g., Levitus 2000). Another important source of variability on multi-decadal scales is the **Pacific Decadal Oscillation (PDO)**, Fig. 4b, <http://www.jisao.washington.edu/pdo/>. PDO phases, defined from the first EOF of sea surface temperature (SST) in the Pacific north of 20° N latitude (Mantua et al. 1997), appear to persist for 20-30 y. On the interannual time scale, **El Niño** is the dominant source of ocean variability in the North Pacific (Fig. 4c, reflected in anomalously positive sea level at San Diego), and an important source of variation in much of the ocean-atmosphere system.

Fig. 4. Different scales of long-term physical forcing recognized in the California Current. (a) Secular trend in temperature recorded at the Scripps pier (record extends

To 1916), (b) Pacific Decadal Oscillation index (annual averages, Mantua et al. 1997), (c) mid-latitude effects of El Niño, reflected in positive anomalies of sea level height at San Diego (upper & lower lines indicate ± 1 s.d.).



These different sources and scales of variability are not independent. Influences of El Niño and the PDO can be seen in the Scripps pier temperature record (Fig. 4a), together with the secular warming trend, underscoring the challenge of resolving processes acting on multiple, interacting temporal scales. Because CalCOFI exists, we have better prospects of resolving these issues in the California Current that nearly anywhere else in the ocean.

In addition to the 20th century water-column record, paleoceanographic approaches have provided remarkable insights into the long-term variability of coastal ecosystems in the CC and elsewhere in the North Pacific. Analysis of fish scales deposited in the layered sediments of the Santa Barbara basin revealed quasi-cyclical variations of sardines and anchovies over the past 1700 y, well before industrial fishing (Soutar & Issacs 1974, Baumgartner et al. 1992). Some of the dominant frequencies of variation may be multiples of the 25-30 y time scale of variation detected in the PDO. An alkenone unsaturation index (Zhao et al. 2000) and the species composition and stable isotopes of shells of planktonic foraminifera and radiolaria from Santa Barbara Basin sediments have revealed other, lower frequency Holocene climate variations (Kennett & Venz, 1995, Weinheimer & Cayan 1997, Field 2004), as has the analysis of salmon-derived stable N isotopes in Alaska lake sediments (Finney et al. 2000, 2002).

Ecosystem Responses: Some of the responses of the pelagic ecosystem to the different time scales of forcing are already recognized, although the mechanisms underlying them are still speculative. In the 52-y record of zooplankton biomass from the CCS, for example, climate influences on interannual and interdecadal times scales are strongly evident (Fig. 5). On the interannual scale, the major El Niños are associated with pronounced biomass declines, although the system usually recovers within 1-2 y. On a longer time scale, biomass declined 70% between the 1950's and 80's (Roemmich & McGowan 1995a,b; see Fig. 5) and was originally thought to be a consequence of the long-term ocean warming. In 1999, however, biomass recovered from an El Niño to levels above the long-term mean, and has remained at this new level for the past five years. This relatively abrupt change coincided with compositional shifts in the zooplankton assemblage and physical changes in the water column (Fig. 5, below), suggesting the beginning of a new PDO phase. Interactions between interannual and multi-decadal time scales are also illustrated in Fig. 5, the coincidence of the strong El Niño of 1997-98, the PDO warm phase and the secular warming trend led in 1998 to the lowest zooplankton biomass in the 48-y record.

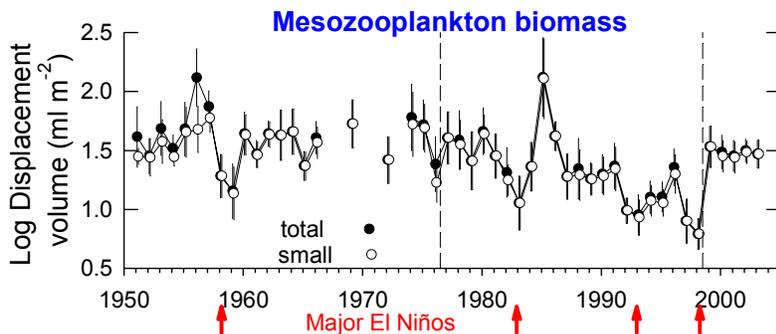
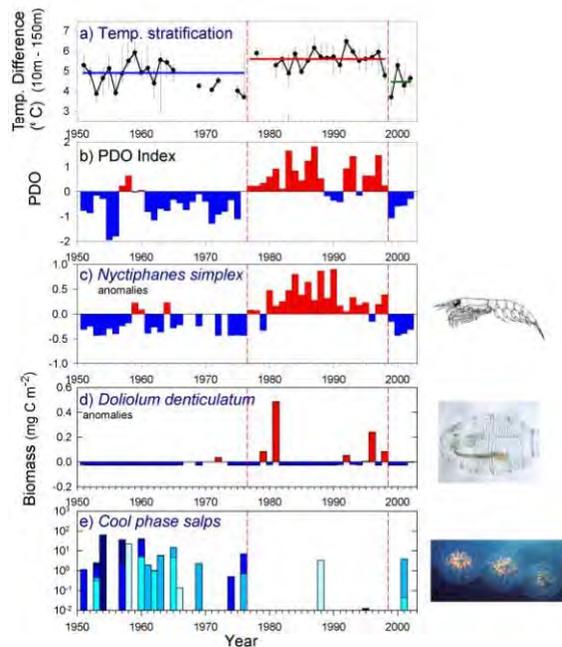


Fig. 5. Variations in springtime zooplankton biomass from CalCOFI cruises in the CCE LTER region. Arrows indicate major El Niños and dashed lines hypothesized nodes in the PDO. (after Lavaniegos & Ohman 2003).

Some responses to PDO-scale forcing have become more clear with recent analyses of zooplankton species from the historic CalCOFI samples (Lavaniegos & Ohman 1999, 2003; Rebstock 2001, 2002; Brinton & Townsend 2003). Figure 6 illustrates the relatively rapid changes between conditions that have been characterized as shifts of different “regimes” (*sensu* Issacs 1976). The 1976-77 transition has been widely recognized as a change point in many atmospheric, physical ocean, terrestrial, and bio-oceanographic time series in the North Pacific (Ebbesmeyer et al. 1991, but see Rudnick & Davis 2003). Note that the mid-1970's shifts in biomass of some species such as the euphausiid *Nyctiphanes simplex* (Fig. 6c) are not reflected in total zooplankton biomass (Fig. 4).

Fig. 6. Multidecadal variation in a) stratification, b) PDO index, c) biomass of the euphausiid *N. simplex*, d) the doliolid *D. denticulatum*, and e) a cool phase assemblage of salps (Ohman & Venrick 2003). Stratification and zooplankton measurements from the CalCOFI program. Vertical lines represent hypothesized nodes in the pelagic ecosystem.

In addition to the mid-1970's shift, the possibility of a more recent transition in 1999 has attracted much interest (e.g., Ohman & Venrick 2003, Schwing & Peterson 2003). Following the El Niño of 1997-98, the PDO changed sign, CalCOFI springtime stratification decreased and many of the faunistic characteristics reversed sign (Fig. 6). The CCS appears to have persisted in this generally cooler state since 1999, despite the mild El Niño of 2002-03, suggesting that 1999 could represent the beginning of a new dynamic regime. Although advective changes could be responsible for *initiating* the ecosystem changes observed here, evidence suggests that variations in advection alone are not a sufficient to explain the *persistence* of the changes through time. We intend to explore the alternative hypotheses that persistent change in *in situ* food web structure, or altered predation pressure, are responsible for maintaining a new dynamic regime.



The altered thermal stratification in Fig. 6a is particularly significant for upwelling ecosystems because stratification intensity can affect the supply of new nutrients from below the thermocline (Roemmich & McGowan 1995). As shown below, variations in the nitracline depth, which are closely linked to vertical stratification, influence production rates and community composition at the base of pelagic food webs.

In addition to zooplankton, populations of small pelagic fishes, including Pacific sardine, northern anchovy and jack mackerel, fluctuate in size and distribution over a range of time scales. The multi-decadal fluctuations of sardine and anchovy, indicated by catch statistics (Fig. 7), are legendary. Moreover, planktivorous fish in coastal pelagic ecosystems around the Pacific basin show remarkable long-term coherence (Kawasaki & Omori 1988, Schwartzlose et al. 1999). Sardines in California, Peru and Japan vary in phase with one another, suggesting similar responses to climate change in disparate regions of the coastal ocean. Hypothetically, major stock variations of these major planktivorous fishes could have significant consequences for standing stocks and species composition of the planktonic food web.

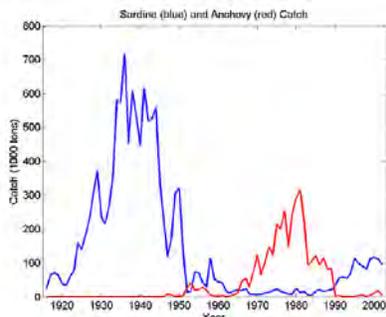


Fig. 7. Variation in 20th century catch of the Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*). Courtesy of the Southwest Fisheries Science Center/NMFS and D.M. Checkley.

Studies of pelagic seabirds in the California Current illustrate that some changes in bird abundance may precede or lag changes of the upper ocean temperature (e.g., Pink-footed Shearwater, *P. creatopus*, precedes warming by 3 months; Sooty Shearwater, *P. griseus*, lags by 6 months; Hyrenbach & Veit 2003). The role of the planktonic food web in such effects requires investigation.

Responses to El Niño Forcing: The El Niño-Southern Oscillation (ENSO) cycle may be the largest climate signal in the ocean, with consequences extending from the tropics to polar regions. In the CCS, coastally trapped Kelvin waves propagate from the tropical Pacific, but atmospheric teleconnections also alter atmospheric (and hence oceanic) circulation. The largest signature of El Niño in the southern CC is generally well below the sea surface, centered at 75-125 m, where anomalously warm, salty water intrudes from the south or west. The thermocline and nitracline are depressed. In the very strong El Niño of 1997-98, the nitracline deepened by 30-40 m (Fig. 8). This response was more subtle during the weaker, protracted El Niño-like conditions of 1992-94.

For the CC pelagic ecosystem, the consequences of nitracline deepening can include reductions in areal extent of enriched standing stocks of phytoplankton (Fig. 9, Kahru & Mitchell 2000), reduced zooplankton biomass (Chelton et al. 1982), poleward displacements of subtropical organisms (Brodeur 1986), reduced growth rate of juvenile fishes (Butler 1989), reduced spawning and/or deeper depth distributions of squid, and effects on seabirds and mammals. A recent study based on CalCOFI copepods found a pronounced decline in percent similarity during some El Niños (Fig. 10, Rebstock 2001). However, these dips in similarity indices were discernable only in El Niños since 1977, despite the existence of a very strong El Niño during 1957-59 and lesser Niño events in other years (e.g., 1966 and 1972). Rebstock (2001) raised the very interesting possibility that the ecological consequences of El Niño are different during the PDO cool phase (e.g., 1951-1976) than the warm phase (1977-1998). **The interactions of processes on multiple time scales may generate unexpected nonlinear responses in the ecosystem.**

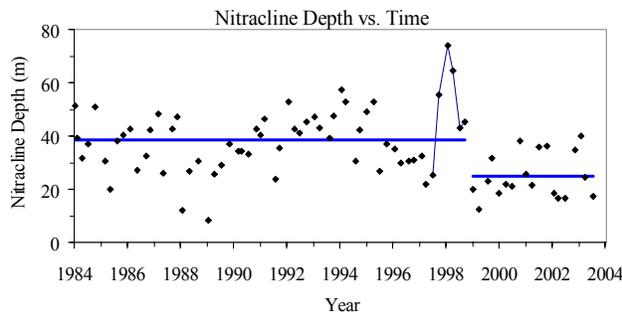


Fig. 8. Temporal variation in the average depth of the nitracline, defined as the first depth where $\text{NO}_3 \geq 1.0 \mu\text{M}$, for the CalCOFI region from the shore out to station 70. Vertical spike in 1997-98 reflects El Niño-related deepening of the nitracline. Horizontal lines illustrate means for 1984-1998 and 1999-2003, again illustrating the suggested ecosystem shift in 1999 (Goericke, unpubl.).

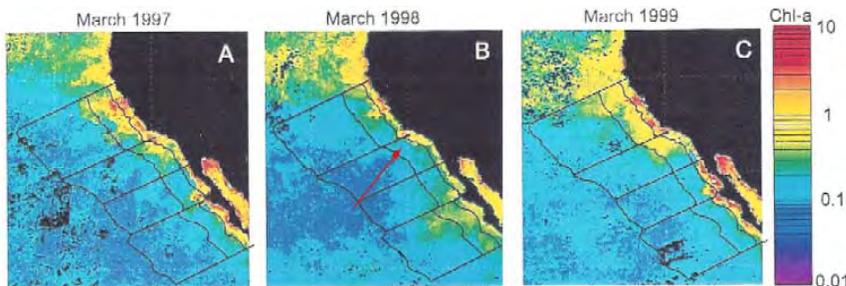


Fig. 9. El Niño effects on the areal extent of the region of enriched phytoplankton pigments in the California Current. SeaWiFS images from a) March 1997 (pre-Niño), b) March 1998 (Niño), c) March 1999 (post-Niño). Arrow in panel b indicates our LTER study region. (from Kahru & Mitchell 2000).

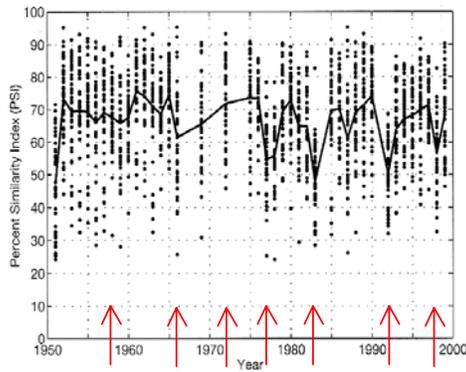


Fig. 10. Time series of percent similarity of planktonic copepod samples (based on 35 taxa) in the California Current, 1951-1999. In each year the similarity of the copepod fauna is compared to every other year; heavy line indicates the median. Rebstock 2001. Arrows indicate El Niño years; note El Niño-related responses after the 1977 “regime shift,” but not before.

Another El Niño response is reflected in the stable N isotopes of two herbivorous copepods and two carnivorous chaetognaths. Three of the four species became isotopically heavier during the major Niño’s in the record (1958, 1983, 1998; Fig. 11). Unlike the copepod similarity index there was no difference between warm and cool phases of the PDO in this effect. Mechanisms that would account for this enrichment in heavy isotopes during El Niño are enhanced utilization of ammonium by phytoplankton or increased carnivory by copepods (Rau et al. 2003). We intend to test these hypotheses in the first phase of our LTER research. Mullin (1991, 1997) detected no decrease in per capita egg

production rates by the copepod *Calanus pacificus* during El Niño’s, suggesting that the dietary shift implied by Fig. 9 does not carry a demographic cost.

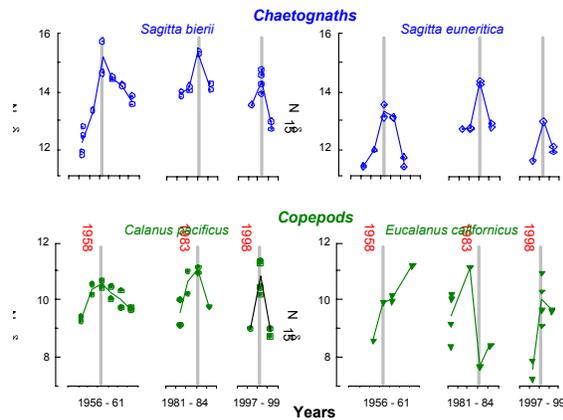


Fig. 11. $\delta^{15}\text{N}$ of two chaetognath species (upper panels, blue) and two suspension-feeding copepods (lower panels, green) in springtimes during major El Niños (vertical lines) and years immediately preceding and following. From CalCOFI samples off central California. Rau, Ohman & Pierrot-Bults (2003).

Spatial structuring of CCS pelagic ecosystems

Mesoscale structure: In addition to the large-scale latitudinal gradients in the CCS, there is rich mesoscale variability, particularly with the development of mesoscale circulation in the spring and summer. Fig. 12 illustrates the highly elevated phytoplankton pigments associated with coastal upwelling (and probably with wind-stress curl upwelling in the more offshore domain), and the rich mesoscale structure of filaments, jets and eddies that typifies coastal upwelling ecosystems.

Fig. 12. GLI ocean color image of southern sector of the California Current (8 April 2003). Red = high, blue = low pigments; white = clouds, brown = land mass. ADEOS II, GLI image courtesy of G. Mitchell, JAXA and the GLI science team.

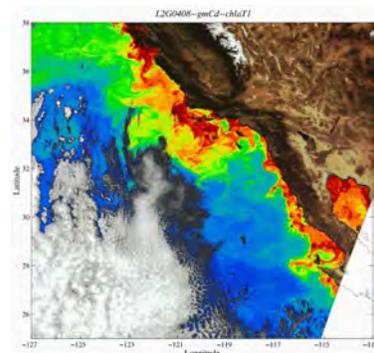
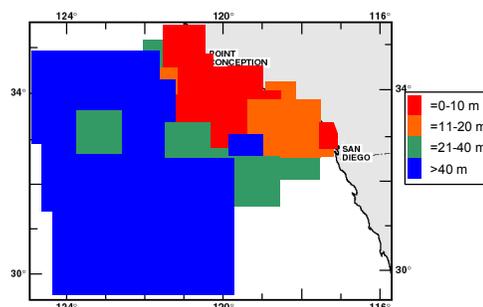


Fig. 13. Depth of nitracline (here, first depth where nitrate $\geq 1.0 \mu\text{M}$), from CalCOFI cruise in April 2003 (King & Barbeau, unpubl.).

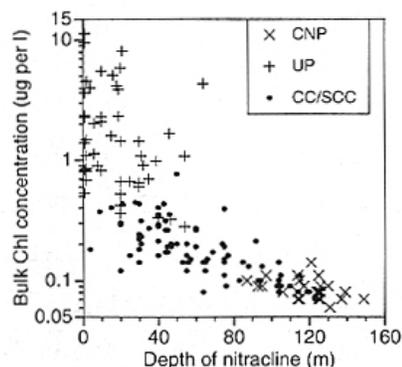


Relationship of phytoplankton assemblages to the nitracline depth:

Because it is related to the vertical stability of the water column and the supply of new nutrients, the depth of the nitracline is an important structuring element for the phytoplankton assemblage. Horizontal variations in the depth of the nitracline in our proposed CCE LTER region show some recurrent features: the deepest nitracline depths are in the well-stratified offshore region, the shallowest are in the region near Pt. Conception and often both west and south of Pt. Conception, and intermediate nitracline depths occur in the Southern California Bight and the core of the CC (Fig. 13).

The total biomass of phytoplankton, represented by bulk Chl *a*, is inversely related to nitracline depth (Fig. 14 from Collier & Palenik 2003; see also Eppley et al. 1978, Goericke [submitted]). Because vertically integrated primary production rates in this region are proportional to vertically integrated Chl *a* (Hayward & Venrick 1982, Mantyla et al. 1995), the total rate of primary production should also be proportional to nitracline depth.

Fig. 14. Relationship between Chl*a* concentration and the depth of the nitracline, from recent CalCOFI cruises (Collier & Palenik 2003). Symbols indicate stations in the region shown in Fig. 10 characterized as Central North Pacific, upwelling region, and



Bulk phytoplankton pigments, while a useful metric for some purposes, mask important structural changes in the phytoplankton assemblage that have consequences for other elements of the food web. Goericke (submitted) has shown that there are predictable shifts in the phytoplankton assemblage with large changes in total biomass (as bulk Chl*a*). Goericke's use of High Performance Liquid Chromatography (HPLC) in the CalCOFI region illustrates that at high chlorophyll concentrations ($>1.0 \mu\text{g Chl } a \text{ L}^{-1}$, corresponding to shallow nitracline depths), phytoplankton biomass variability is strongly associated with diatoms (Fig. 15a) and inversely

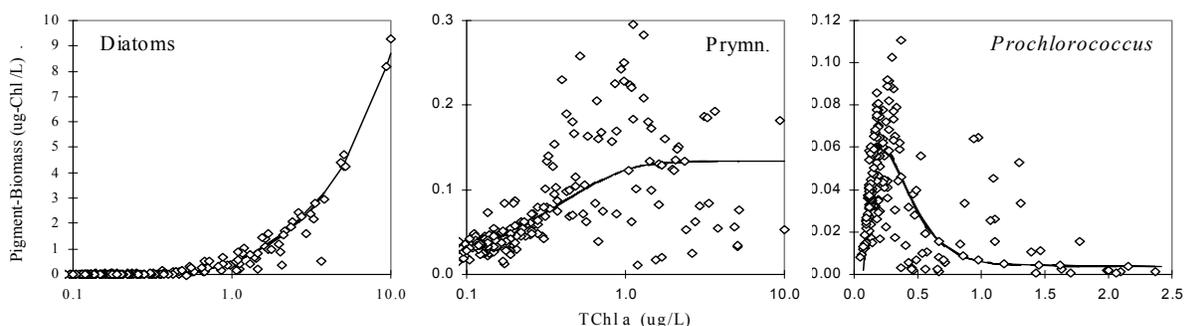


Fig. 15. Relationship of biomass of particular phytoplankton taxa to total Chl*a* biomass, as determined by HPLC analysis from samples in the CalCOFI domain. a) diatoms, b) prymnesiophytes, and c) *Prochlorococcus* (Goericke, subm ms.).

related to variations in biomass of the photosynthetic cyanobacterium *Prochlorococcus* (Fig. 15c). However, at concentrations of total Chla $< 0.3 \mu\text{g L}^{-1}$, *Prochlorococcus* varies in direct proportion to Chla concentrations. A similar curvilinear relationship has been observed for the cyanobacterium *Synechococcus* (Collier & Palenik 2003). Prymnesiophytes show a proportionality at low-to-intermediate concentrations. Goericke (subm.) has also suggested that picoplankton show a relatively modest range of variation in biomass through space and time, and that the major dynamical variation in phytoplankton community structure originates with the larger forms.

These results suggest that **variations in nutricline depth and associated changes in total biomass and phytoplankton community composition are important organizing principles for both the spatial and temporal variations in food web structure in our proposed LTER site**. Clearly, other nutrients and micronutrients can also influence community changes. In addition to nitrate, silicic acid, phosphate, iron (see below) and other trace metals, can also be important factors influencing the structure and composition of phytoplankton assemblages and will also be investigated in this LTER program.

Floristically defined regions of the CCS: Detailed floristic analyses by microscopy have revealed distinct regions in this sector of the CCS within which the flora varies coherently over time (Venrick 1998, 2002, Hayward & Venrick 1998). The larger of these – the offshore region (Fig. 16b) - and the northern inshore region (Fig. 15a) are separated by a boundary region that is defined by the core of the California Current and which meanders longitudinally over time. In the boundary region, the flora has relatively little temporal coherence with adjacent stations. It is important to realize that the boundary region is actually rather narrow at any instant in time.

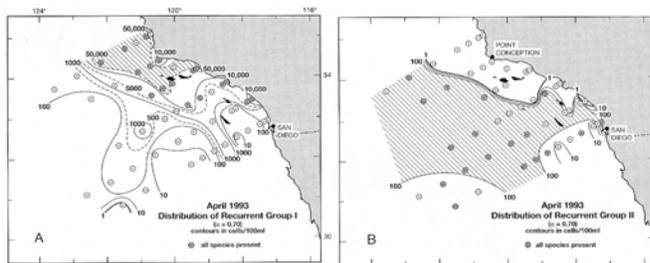


Fig. 16. Recurrent groups of phytoplankton in April 1993 (Venrick 1998) a) Distribution of Recurrent Group I and b) distribution of Recurrent Group II. At this point in time, a northern inshore flora was separated by an offshore flora by a narrow boundary along the inshore edge of the California Current. Note the effect of the prominent eddy, which transported inshore flora far into the offshore zone.

We intend to use the three principal floristic regions identified in Fig. 16, including the boundary region, to guide the Experimental Process Studies defined below. The differences among these subregions in density stratification, rates of upwelling, nitracline depth, dominant phytoplankton taxa, and grazer populations, are excellent analogs for the temporal variation in these same ecosystem characteristics.

Iron limitation of phytoplankton growth: Within our LTER domain, regional patterns in phytoplankton biomass and community composition are broadly correlated with the extent of macronutrient enrichment in near-surface layers caused by isopycnal shoaling (e.g., Hayward & Venrick 1998, Venrick 1998, Mullin 2000). While nitrate has been the critical nutrient considered in these studies, there is evidence to suggest that, in addition to nitracline shoaling, iron distributions may also play a role in structuring the phytoplankton community in the southern California region, in addition to nearby coastal upwelling regimes of the northern and

central California Current (Hutchins & Bruland 1998, Hutchins et. al. 1998, Johnson et. al. 1999, Bruland et. al. 2001). In the central coast region, the supply of iron relative to that of the macronutrients nitrate, phosphate, and silicate is important in determining the extent to which coastal blooms of large diatoms can form during spring and summer upwelling. It is likely that similar forcing related to iron supply affects the phytoplankton community in the southern California region.

For example, recent data from Fe-addition incubation experiments carried out by co-PI K. Barbeau's group in conjunction with the CalCOFI program shows a significant regional pattern in the extent of Fe stress in the phytoplankton communities of the southern California Current (see Figs. 17 & 18). "Grow-out" incubations conducted during spring 2003 (Fig 16) suggest that Fe stress becomes more acute as upwelling water masses move offshore. A time course experiment illustrates the marked effect of Fe additions on growth rate and on draw down of nitrate (Fig. 17). Changes in the phytoplankton assemblage also accompany these changes in total phytoplankton biomass.

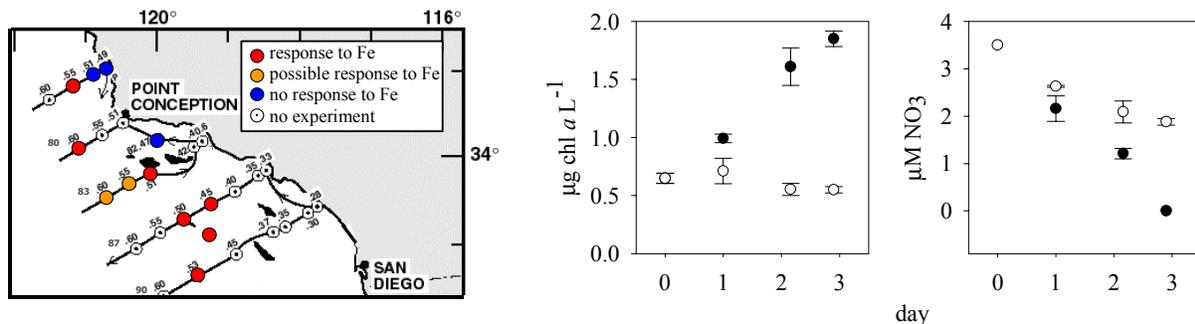


Fig. 17 (left). Results of Fe-enrichment experiments during the 4-25 April 2003 CalCOFI cruise. Response to Fe is measured as significant differences in Chl *a* concentration between +Fe treatments and unamended controls. Chl *a* net growth rates were, on average, ~2-times faster in +Fe treatments. Results from 2 stations were inconclusive (King & Barbeau, unpubl.).

Fig. 18 (right). Results from Fe-addition incubation experiment at station 77.55 on 29 July 2003. Left: Chl *a* (μg L⁻¹; ○=control, ●=+Fe) and Right: dissolved NO₃ (μM; ○=control, ●=+Fe). Chl *a* net growth rate was 4 times faster in +Fe incubations (King & Barbeau, unpubl.).

The regional pattern of Fe limitation in the southern California Current regime is likely to vary on interannual timescales with the El Niño-Southern Oscillation cycle (cf. Johnson et al. 1999, Mullin 2000). These changing Fe dynamics are likely to contribute to changes in the phytoplankton community.

Ecosystem consequences of changes in community structure

Some of the changes in pelagic community composition noted above will also alter the functional characteristics of the ecosystem. For example:

Pelagic coupling to the deep sea benthos: The previously documented long-term decline in biomass of epipelagic zooplankton in the CCS (Roemmich & McGowan 1995a, b) may have had consequences extending far beyond the coastal ocean, to the deep sea. The zooplankton decline is now believed to be largely attributable to a decrease in salps and other pelagic tunicates (Lavaniegos & Ohman 2003). This decline was coincident with a decreased flux of particulate organic carbon (POC) to the deep-sea floor (approximately 4,000 m below the sea surface, Smith

& Kaufman 1999, Smith et al. 2001). Notably, the decline of zooplankton biomass reversed in 1999, some salp species have returned (Lavaniegos & Ohman 2003), and deep-sea POC fluxes have recently increased (Ruhl et al. ms.). As salps are known to produce fecal pellets that sink disproportionately quickly in relation to their size (e.g., Bruland & Silver 1981), the composition of epipelagic zooplankton may modulates fluxes through the 4-km water column.

El Niño effects on growth rates of fishes: The growth rates of juvenile northern anchovy decline in major El Niño's (Butler 1989). Presumably this decline is related to changes in the prey field, including decreases in zooplankton biomass (Chelton et al. 1982, Lavaniegos & Ohman 2003), changes in lower food web trophic structure (Rau et al. 2003), and alterations to the composition of the copepod assemblage (Rebstock 2001).

Domoic acid production by harmful algae: The neurotoxin domoic acid (DA) is produced by several species in the diatom genus *Pseudo-nitzschia* and has been implicated in mass mortalities of marine birds (Work et al 1993) and mammals (Scholin et al. 2000). In pelagic ecosystems, a major transfer vector appears to be the small pelagic fish, such as sardines and anchovies, which can have large amounts of DA in their guts but do not readily absorb the toxin themselves. Recently, it has been suggested that anchovies, being generally more herbivorous than sardines, are more likely to be contaminated than sardine and thus pose the greater risk (Lefebvre et al 2002, Altwein et al 1995). As anchovy populations appear to be sensitive to interdecadal climate shifts, this raises the interesting possibility that mortality from blooms of the diatom *Pseudo-nitzschia* spp. and associated DA poisoning is more prevalent during warm-water periods. Rue & Bruland (2001) and Maldonado et al. (2002) have shown that DA is produced by the diatoms during Fe and Cu stress, and may serve as a metal-binding ligand. Thus, changes in Fe availability noted above may have consequences for the coastal megafauna.

Top-down structuring of coastal pelagic ecosystems: Much of the preceding discussion of the temporal and spatial variability of pelagic ecosystems has emphasized a 'bottom-up' perspective. This is in large part determined by the evidence that physical climate signals, particularly on the El Niño and the PDO time scales, alter these food webs. Nevertheless, at least two of the PI's of the present proposal have for more than two decades published on the importance of predation in influencing behavior and life histories of planktonic organisms, as well as the structure and composition of plankton communities. We maintain an open mind about the importance of biotic interactions, and predator-prey interactions in particular, in shaping pelagic ecosystems.

Issacs (1972) proposed that marine pelagic food webs are relatively "unstructured," implying widespread omnivory at most trophic levels. If correct, omnivory would modulate the tendency for strong trophic interactions to propagate to the base of oceanic food webs. This may represent a structural contrast with pelagic lake ecosystems. In comparing pelagic marine with pelagic lake ecosystems, the paucity of spatial boundaries and large spatial scale of circulation systems in the ocean pose the question: do the strong trophic interactions found in many lake ecosystems (e.g., Carpenter & Kitchell 1993) also scale to pelagic marine ecosystems? These are compelling issues that we look forward to addressing with colleagues in the LTER program.

Unifying Theme and Approach

The preceding discussion has illustrated that many aspects of the variability in the coastal pelagic ecosystem of the CCS have already been characterized, at a variety of temporal and spatial scales. Among the temporal scales, the most notable are longer-term phenomena:

interannual variations associated with El Niño, PDO multi-decadal variability, and perhaps a multi-decadal secular trend. The responses of several key taxa within pelagic ecosystems to such forcing have been documented, especially at the level of the mesozooplankton, marine fishes, and seabirds. However, while we have rich descriptive information regarding the transitions between different dynamic states of the California Current Ecosystem (CCE) and preliminary hypotheses as to causality have been advanced, we have not resolved the *mechanisms* that generate such transitions and maintain different ecosystem states. In what follows, we develop the overall theme for the CCE LTER site, which is to resolve the mechanisms leading to transitions between different ecosystem states.

The central questions we will address in the CCE LTER site are: ***What are the mechanisms leading to different ecosystem states in a coastal pelagic ecosystem? What is the interplay between changing ocean climate, community structure and ecosystem dynamics?***

Hypothesized mechanisms of California Current pelagic ecosystem shift

We identify four principal mechanisms that could lead to the previously observed El Niño and PDO-related ecosystem shifts in the California Current pelagic ecosystem:

- ✦ **Sustained, anomalous alongshore advection of different assemblages** -- Temporal variations in north-south transport introduce organisms of different geographic origins into the southern sector of the CCS.
- ✦ **In situ food web changes in response to altered stratification and nutrient supply** Changes in the species structure, trophic connections, and pathways of energy flow occur in response to changes in water column vertical stratification. Stratification modifies the rate of supply of limiting nutrients for phytoplankton production. Altered nutrient supply (whether macronutrients [e.g., NO_3^- , $\text{Si}(\text{OH})_4$] or trace metals [e.g., Fe]) leads to altered rates of primary production and/or compositional changes in the phytoplankton assemblage, which propagate through the food web.
- ✦ **Changes in cross-shore transport and loss/retention of organisms** -- Temporal changes in the rates of cross-shore transport modify the probability of retention of nutrients and organisms in the nearshore coastal zone.
- ✦ **Altered predation pressure** -- Altered abundances (or dietary shifts) of planktivores lead to selective mortality and altered abundances and composition of the planktonic food web.

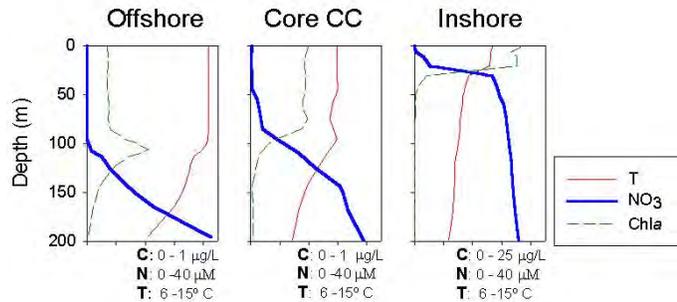
We propose to evaluate each of these hypotheses in the first six years of our LTER site, although the approaches taken will differ. Our initial *experimental* focus will be on the hypothesis of ***in situ* food web changes**, as described in detail in the subsequent proposal section. The remaining hypotheses (changes in **alongshore advection**, **cross-shore transport/retention** of organisms, or **predation pressure**) will be evaluated through time-series measurements and modeling studies, as described below. We fully recognize that these hypotheses are not mutually exclusive, and the central issue may well be the relative importance of each of these different hypothesized mechanisms.

Approaches to address alternate hypotheses

Experimental studies capitalizing on spatial analogs of temporal change: Given the present unpredictable nature of ecosystem changes, we cannot be assured of capturing an appropriate

transition even over the course of our first six years. The recurrence interval of ENSO is 3-7 years and some ENSO events detectable in low latitudes do not have measurable consequences in the mid-latitude ocean. The recurrence interval of PDO shifts is not clear, but appears to be on the order of 20-30 y. In order to address the hypothesis of *in situ* food web changes in the face of this temporal uncertainty, we will exploit the spatial variability in the southern sector of the CCS and the wide dynamic range of ocean conditions that exist at any given time within our study domain. These conditions range from the productive nearshore coastal upwelling region off Pt. Conception to the highly oligotrophic, stably stratified region on the edge of the central North Pacific Gyre (Fig. 19). The spatial range of phytoplankton biomass variations encompasses most of the dynamic range

Fig. 19. Spatial difference in Temperature (T), NO₃ and Chla concentration, in 3 regions of the CalCOFI domain: inshore upwelling, Core California Current, and stably stratified offshore. Note changing scale of Chla. (E. Venrick, unpubl.)



of conditions in the ocean (Kahru & Mitchell 1999).

Many of the El Niño-associated changes that have been observed in this region, including increased temperatures, deepened thermocline, deepened nitracline, reduced productivity, etc., have clear spatial analogs. Therefore, we will utilize the broad dynamic range of conditions that we observe in different spatial regions to investigate the different food web structures and rate processes that underlie variations through time. For our experimental process studies we will focus on different characteristic spatial regions, defined by phytoplankton floristic analyses and water column characteristics, representing the end-member states of pelagic ecosystem structure (strong upwelling to stably stratified) and a continuum of conditions in between. We will simultaneously carry out time series measurements that will enable us to test the assumption that variations in space are appropriate analogs for variations in one region over time.

A primary organizing principle that determines the characteristics of the base of the food web is the depth of the nitracline, as illustrated in section I. Temporal variations in nitracline depth documented previously by CalCOFI (Fig. xx above) are in the sensitive range where shifts from one dominant assemblage to another are likely to occur (Fig. xx, cf. Collier & Palenik 2003, Goericke subm). We will specifically study regions of different nitracline depths and phytoplankton assemblages in order to understand the different food web structures present and the different growth and loss rates. Our objective will be to develop continuous functions that represent quantities such as growth and grazing rates of different members of the plankton assemblage, expressed as a function of the independent variable nitracline depth. These functions will then be used in our coupled bio-physical models to simulate the ecosystem effects of changes in nitracline depth over time, initially focusing on El Niño.

An important parallel between the PDO and ENSO should be recognized. In defining the PDO, Mantua et al. (1997) pointed out that the spatial imprint of the warming associated with the positive phase of the PDO is quite similar to the spatial imprint of El Niño: a broad horseshoe-

shaped pattern of warming at the eastern margin of the NE Pacific and cooling in the ocean's interior, although the persistence time for the PDO is much longer (2-3 decades) than that of El Niño. The similarity in geographic pattern of the positive phase of ENSO and the PDO suggest that the ecological conditions in one will be informative with respect to the other.

Hypothesis of anomalous alongshore advection: The importance of sustained, anomalous alongshore advection as a mechanism leading to changes in assemblages and maintain altered assemblages will be addressed by calculating the north-south volume transports through the cross-shore trending lines in the LTER sampling domain. Vertically integrated transports to a depth of 200 m will be computed from the dynamic topography obtained on quarterly time series cruises to assess whether altered fauna is coincident with altered transports. Higher frequency sampling by the nearshore NDBC moorings, SIO pier measurements, and Ocean Institute near-daily profiles will permit finer temporal resolution of transitions. Calculations of property fluxes using the "Control Volume" approach, as described below, will provide a constraint on the accuracy of the volume transport calculations.

Hypothesis of anomalous cross-shore transport and loss/retention of organisms: Altered cross-shore transports as a mechanism leading to altered rates of retention of organisms in the near-shore zone will be addressed by inferring the rates of Ekman transport from the near-surface wind field measured on CalCOFI cruises. Calculations of property fluxes using the Control Volume approach, as described below, will provide a constraint on the accuracy of the volume transport calculations.

Hypothesis of altered predation pressure: The predators of primary interest are the zooplanktivorous fishes and carnivorous zooplankton. Variations in zooplanktivorous fish stocks (sardines, anchovies, jack mackerel) will be determined by colleagues at the Southwest Fisheries Science Center/NMFS. Stock sizes of sardines and anchovies will be estimated by the egg production method (Lasker 1985). The NMFS annual aerial survey will be used to estimate relative age structure and distribution of schools of the three principal coastal pelagic species. Bioenergetic models will be used to estimate consumption by fish schools under high and low prey availability that may result from changes in stratification (e.g., Nonacs et al. 2001). Variations in abundances of carnivorous zooplankton (esp. jellyfish, siphonophores, chaetognaths) will be assessed from the CalCOFI zooplankton samples.

Core LTER Research Areas

In the course of our hypothesis-oriented research in the CCE LTER site, we will address core elements held in common among all LTER sites. We particularly look forward to interactions with colleagues who work on biomes very different from coastal pelagic marine ecosystems, and view this as an opportunity for intellectually stimulating exchange. The commonalities and differences with respect to the following properties will be fascinating to explore:

Pattern and control of primary production: Rates and patterns of primary production will be measured by ^{14}C uptake incubations on four cruises per year in our LTER site. Such measurements have been made since 1984 in the CalCOFI region, although for the LTER program we will measure the rate of production of *dissolved* as well as *particulate* organic carbon. In addition to *in situ* measurements, we will explore the utility of advanced algorithms to estimate primary productivity (Behrenfeld & Falkowski 1997, Kahru & Mitchell 2002) and

other ocean optical properties (Stramski et al. 1999, Kahru & Mitchell 2001) from satellite remote sensing.

Investigations of controls of primary production will include the effects of macronutrient limitation, iron limitation, and irradiance on phytoplankton specific growth rates for several algal subgroups. The role of grazing pressure by nano-, micro-, and meso-zooplankton will be addressed on experimental cruises.

Spatial and temporal distribution of populations selected to represent trophic structures: We will focus on representative organisms representing different trophic levels as well as “sentinel species”, many of which are already known to provide excellent indications of responses to ecosystem changes in the CCS. These organisms will be sampled or sighted (seabirds) four times per year on the CalCOFI sampling grid, characterizing spatial as well as temporal variability. They are: **Bacteria** - heterotrophic prokaryotes; **Phytoplankton** - *Synechococcus*, selected diatom and dinoflagellate species; **Suspension-feeding zooplankton** - selected species of copepods, salps and doliolids; **Omnivorous zooplankton** - selected euphausiid species;

Carnivorous zooplankton - selected hydromedusae and siphonophore; **Zooplanktivorous fish** - Pacific sardine, northern anchovy and jack mackerel; **Seabirds** - Sooty Shearwater, Cassin's Auklet, Rhinoceros Auklet, Cook's Petrel and Black-vented Shearwater.

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

Pattern and control of organic matter accumulation and decomposition in surface layers and sediments: Sedimentary accumulation and decomposition of organic matter will not be a major theme in this site, as the principal focus is on the water column. However, interesting circumstantial connections have already been made between the community composition of the epipelagic zooplankton and the flux of Particulate Organic Carbon to sediments in the deep sea (deep sea flux program at Ken Smith's Sta. M, located just north and west of our LTER site). In our LTER study we will explore more explicitly the ways in which the zooplankton community modulates the types of organic matter reaching the sea floor. See attached letter from K. Smith.

Patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters: Fluxes of nutrients are a central issue in this site and will be addressed in our time series studies, experimental studies, and modeling efforts. Time series observations, again on the quarterly augmented CalCOFI cruises, will assess spatial patterns of nutrient concentrations and nutricline depths as well as nutrient input into the euphotic zone via upwelling and horizontal transport. Experimental studies will evaluate sensitivity of different parts of the phytoplankton assemblage to limitation by macronutrients and iron. Control Volume calculations will evaluate the dynamic balance between geostrophic convergence into our study site and Ekman divergence out of our study site, permitting us to constrain the major sources and sinks of nutrients in this system (e.g. Roemmich 1989, Bograd et al. 2001). We are particularly interested in whether the primary form in which N is exported from this region is in the particulate or dissolved phase, and whether this changes during El Niño and other climate forcing.

Patterns and frequency of disturbances: Disturbance influences are fundamental to this LTER site. We will characterize disturbances on many scales, using (1) continuous measurements from the Scripps pier and in cooperation with other, moored measurement programs in the Southern California Bight, (2) nearly daily CTD and phytoplankton pigment profiles from our Education and Outreach partner, the Ocean Institute, located in Dana Point, CA, (3) satellite remote sensing measurements, with particular emphasis on MODIS ocean color and sea surface temperatures, (4) quarterly shipboard measurements of a suite of hydrographic, meteorological, plankton, ichthyoplankton characteristics, and (5) communication with colleagues who use paleoceanographic proxies (fish scales, foram abundances and stable isotopes, alenone unsaturation) to characterize longer term variability from the Santa Barbara and nearby basin sediments.

While the emphasis in this proposal has been on longer-term, lower-frequency disturbances, the temporal “event” scale and the spatial mesoscale are also known to influence plankton dynamics at this LTER site. We recognize that the mode of action of some longer-term disturbances may be through altered patterns or frequencies of smaller-scale phenomena (e.g., altered patterns of upwelling-favorable wind events during El Niño).

Advantages of the Southern Sector of the CCS as an LTER site

The Southern sector of the CCS, from just north of Pt. Conception to the Mexican border and from the shoreline offshore (**Fig. 22**) is an ideal location for an LTER site for many reasons:

1. Building on a **the CalCOFI foundation**. In its 55th year, CalCOFI is the longest comprehensive oceanographic time series in the ocean; it has already revealed several important scales of response of coastal ocean ecosystems and is poised to probe the mechanistic basis for these changes.
2. The study site encompasses a **biogeographic boundary region** and is an early sentinel of climate change.
3. **Parallels with other coastal upwelling biomes**. The CCS is an excellent representative of coastal upwelling biomes on the eastern margins of major ocean basins. They are among the most productive pelagic coastal ocean ecosystems and support a variety of fisheries of finfish and invertebrates.
4. This is **the preferred spawning site for ~90% of epipelagic fish biomass** (hake, sardine, anchovy; EBC report 1992) in the southern sector of the CCS, as well as for many nearshore fishes and benthic invertebrates.
5. **Spatial coherence:** low frequency changes in the southern sector of CCS are correlated with changes in much of the NE Pacific (McGowan et al. 1998).
6. **High dynamic range of ocean conditions**, from oligotrophic to high productivity, occur over a small geographic distance, encompassing much of the range in the world ocean.
7. **Paleoclimate studies** in the unusual anaerobic, varved sediments of the Santa Barbara Basin provide an unusual paleoceanographic context for this LTER site.
8. **A dynamical, 4-D physical ocean circulation model** is already in place (Miller et al. 2000); it will be a natural progression to couple biological models to develop a state of the art, coupled physical-ecosystem model.
9. **Access to SIO Oceanographic Collections** for retrospective (and prospective) studies of pelagic ecosystems

10. The **Channel Islands National Marine Sanctuary** is within our study domain and the local marine communities are directly affected by the processes we will investigate.

Regionalization and Interrelationships with other programs

11. We will provide an **oceanographic connection to the Santa Barbara kelp forest LTER site**; our studies of the larger scale circulation and variations in nitracline depth will improve predictability of oceanic forcing affecting the coastal kelp forest.
12. Opportunity for **comparative studies with other pelagic programs**, including North Temperate Lakes and Palmer Station, as well as sites exploring multiple stable states and ENSO responses.
13. **Coupling to the benthos**; Ken Smith's benthic time series is located just N and W of our study domain, and provides a linkage between upper water column processes and the deep-sea benthic community.
14. **Connection to other N. Pacific programs**, including Baja California studies (IMECOCAL) and the developing PaCOS (Pacific Coastal Observing System) group
15. Excellent opportunities for **linkages with other coastal ocean programs** (incl. SCCOOS, PISCO)
16. **Excellent scientific interactions with SWFSC** (NOAA's Southwest Fisheries Science Center), 2 of whose scientists are Associates on this proposal.
17. **Association w/ Birch aquarium and COSEE** for highly effective communication with the public and education/outreach.
18. Linkage w/ Scripps' **Center for Marine Biodiversity and Conservation**, and a new IGERT for innovative graduate training in marine biodiversity issues.

Components of the California Current Ecosystem LTER program

The California Current Ecosystem (CCE) is a coastal upwelling biome forced by physical processes on a variety of time and space scales. Our LTER site objectives are: to understand the mechanisms leading to transitions between dynamic ecosystem regimes; to understand the relationship between pelagic community structure and ecosystem dynamics; to build synthetic models that will enable us eventually to forecast future trajectories of this pelagic ecosystem in response to a changing climate; and to establish a basis for comparative ecological studies with other marine, lacustrine and terrestrial biomes. We will pursue these objectives with the following program elements:

- **Experimentally-oriented Process Studies** will focus initially on one specific hypothesis leading to ecosystem transitions, i.e., changes in food webs in response to altered stratification and nutrient supply. Details of these studies are described in the following section.
- **Sustained Time-Series Measurements** will enable us to evaluate hypotheses related to a) anomalous alongshore transport, b) cross-shore transport, and c) altered predation pressure. The rich framework provided by the *quarterly CalCOFI time series* provides an excellent backbone upon which to build at modest cost, with appropriate augmentation and modernization. *Satellite remote sensing* will be fundamental to developing nearly continuous measurements of ocean pigments and SST, to resolve transitions, and to provide spatially interpolated fields for data assimilative modeling. *Nearshore measurements* established by others at several locations in the nearshore zone, together with our nearly daily measurements in collaboration with the Ocean Institute, will permit resolution of Kelvin wave passage and other, higher frequency

forcing. Distributional fields from TS-measured parameters will comprise strong system constraints for testing, tuning and validating coupled physical-biological models.

➔ **Modeling.** The models and analyses will provide: i) a mathematical structure for quantifying the dynamics underlying the observations, ii) a synoptic environmental context for point observations, and a means for dynamic interpolation between observations in space and time, iii) a platform for hypothesis testing through numerical experiments and process models, and iv) guidance in the optimization of the sampling program. An existing 3-D physical model for the N Pacific, containing a high-resolution representation of the LTER site will be coupled to a new ecosystem model, formulated and parameterized from results of the field program. Models and data will be analyzed using nonlinear techniques, and data will be assimilated into the models for forecasting. Inverse techniques will allow recovery of model parameters and initial conditions, and process models will be used to explore the relative influence of different hypotheses identified above. “Control volume” calculations will provide property budgets and constraints on regional primary production.

➔ **Data and information management.** The data management plan, coordinated by an expert information manager, will serve data and metadata i) among CCE investigators, ii) between the CCE site and other LTER sites, iii) to resource management and policy professionals, and iv) for our education and outreach efforts.

➔ **Education and outreach.** An education and outreach coordinator based at SIO, working with COSEE and the Birch aquarium, will ensure that research activities at the CCE LTER site are fully integrated with educational opportunities at all levels and outreach to the community. Our goal is to communicate broadly both the *process* of science as well as the *knowledge* gained at our site to the “K-through-grey” communities.

The interrelationships of these program elements may be seen schematically as follows:

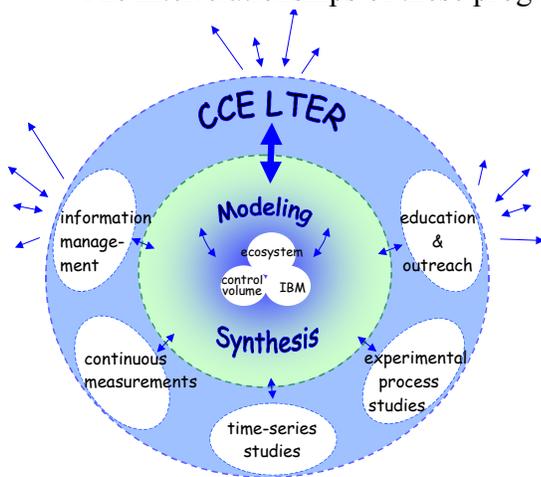


Fig. 20. Conceptual view of the components of the proposed California Current Ecosystem (CCE) LTER site. Results from field components and from models flow into a synthetic commons to which information management and education/outreach also contribute. Continuous measurements include satellite remote sensing and nearshore moorings; time-series studies include augmented quarterly CalCOFI cruises; experimental process cruises are focused on the hypothesis of food web shifts. Arrows outside the immediate CCE site circle indicate the serving of information to the outside world, as well as indicating the bidirectional nature of connections to the LTER network and associated partners.

Experimental Process Studies

As described in the Unifying Theme for this proposal, Process Studies will focus on the mechanisms of community response to short- and long-term changes in the CCE. In the short-term, we seek to understand responses at the base of the food web. Such responses, involving organisms with doubling times on the order of one day, occur on the scale of days, and are

therefore tractable by experimental studies that can be done many times over during the course of a typical research cruise. Lower food web responses give the system its texture, as can be visualized, for example, in the complexity of a satellite ocean-color image of the California Current. In a fully realized, eddy-resolving, coupled physical-biological model, we would hope to understand the dynamics and interactions of this portion of the community sufficiently well to reproduce not only the general spatial patterns of such images and their temporal changes, but also their implications for the gross composition and structure (by size class or major functional groups) of the underlying community. In the long-term, we seek to unravel the relative roles of different mechanisms on the patterns of distribution and abundance of key “sentinel” species, indicators of long-term system change. This implies a different kind of experimental tactic, one in which the goal is to gradually piece together the various behavioral, physiological and life-history attributes of relatively long-lived species that define their interactions in and population dynamic responses to their temporally and spatially variable natural habitat. Although both types of experimental, process-oriented foci are incorporated into the research plan outlined below, it is important to distinguish their different timelines. Whereas, it is reasonable to expect rapid progress in our understanding of the coupled physical-biological dynamics of lower trophic levels, this would be only the starting point for considering the implications of past (retrospective) and potentially future changes in climate and environment at the level of important species. Thus, specifics of the research plan (timing, station selection, etc.) are driven by the desire to optimized progress on short-term objectives.

General Cruise Plan: Experimental Process (EP) cruises will exploit spatial variation within the California Current as a natural analogue of temporal (past and future) variation. Given the hypothesized link between food web changes, local stratification and nutrient availability, we specifically aim to conduct at least initial experimental studies over the broadest range of stratification/nutrient conditions possible. Two to three cruises are planned for this cycle of LTER funding. The first is scheduled for Spring '06 (YEAR 2), spring being the season of highest variability and system richness. The second is scheduled for Late-Summer/Fall '07 (early YEAR 4), the season of strongest mean stratification, although a range of conditions still exist from onshore to offshore stations. Each of these cruises will be of 30-d duration. Given the vagaries of El Niño/La Niña oscillations, we have also requested ship-time for a shorter (20 d) third cruise in YEAR 3 or 5. Should a major event-scale perturbation occur in either of these years, this contingency cruise gives us the flexibility to investigate its consequences, in comparison to the “normal” seasonal range of conditions.

Within the natural range of conditions on the two seasonal cruises and the possibility of sampling an El Niño/La Niña event, we expect to have conducted a sufficient number of field experiments (24-32 station locations, 192-256 depths) to quantify how different components (size classes or functional groups) of the microplankton community respond to local environmental conditions and to test for regularities reflecting system-level, functional response relationships (i.e., those that transcend the effects of individual species, specific locations, seasons or “events”). We illustrate this concept below with an example of class-specific phytoplankton growth rates determined by the pigment labeling technique on two cruises in the Arabian Sea (Fig. 21). Despite being a region of enormous physical and biological variability, ranging from highly dynamic coastal upwelling to ultra-oligotrophic oceanic conditions, and subject to strong seasonal monsoon forcing, there are clear system-level relationships between growth rate and nutrient concentration and differences among groups. These are readily parameterized with Monod-growth kinetics and could provide useful input for a regionally focused model.

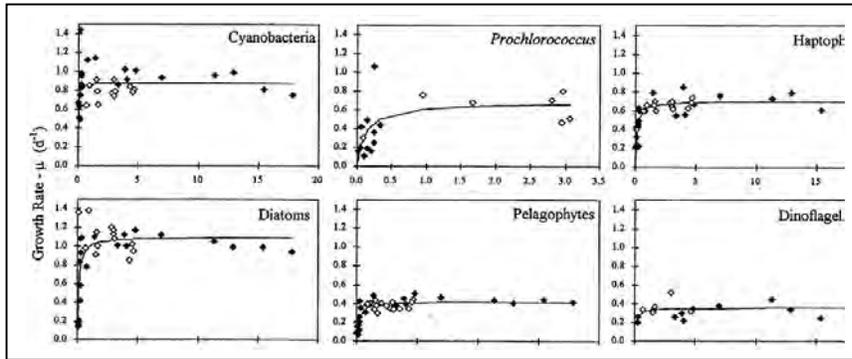


Fig. 21. Taxon-specific growth rates of phytoplankton during the NE (open symbols) and SW (closed) Monsoons in the Arabian Sea. Data are from incubations at high light (36 and 60% surface I). (Goericke 2002)

Understanding (or predicting) how community biomass and composition vary in response to changing conditions requires more than population-specific NO_3 -growth functions at saturating light. Minimally, we need to account for taxon differences in declining growth at lower light (depth), the possibility that other trace or major nutrients (e.g., Fe, P, Si) might be limiting to some or all taxa, and most importantly, the rates of major loss processes. Since net rates of population change, determined from the balance of growth and losses, is typically small relative to maximum growth potential, all of the above factors can greatly influence the relative rates of change of the communities component populations as conditions vary. Evaluating these rate processes and effects is the major objective of the EP cruises.

Sampling and experimental studies are planned for stations of ~ 1.5 -1.8 d duration with a repeat cycle of 2 days. Ship transit time between stations is the variable, but daily satellite images and drifter trajectories will be used to define areas of interest and move efficiently from one to the other. This strategy allows ~ 12 stations to be occupied during a typical 4-week cruise. Due to its high variability, the logical starting point for station operations is in the northern portion of the CalCOFI grid (Point Conception area). The more highly stratified stations are offshore and to the south.

Station operations will begin predawn, with the launch of a mixed-layer drogued surface drifter and CTD/Go-Flo hydrocasts to define initial conditions of the system (depth profiles of all CTD variables, nutrients + Fe, particulate and dissolved C&N, HPLC-measured pigments, and pico-to-microplankton composition; see Table A1 in Time-Series Section) and to collect experimental seawater at 8 light depths spanning the euphotic zone. For each depth, growth/grazing experiments will be started at sunrise and incubated at *in situ* temperatures and light conditions on a drift array: 1) **Pigment labeling experiments** (Goericke & Welschmeyer 1993a) will measure the uptake of ^{14}C (primary production) into particulate and dissolved organic fractions, the instantaneous rates of growth (μ) of the major phytoplankton groups defined by pigments (as above), and the mean C:Chl ratio for the phytoplankton assemblage. 2) **Dilution experiments** (Landry & Hassett 1982), modified for 2 treatments, will provide complementary estimates of growth rate (μ) for pigment as well as flow-cytometrically and microscopically (size) defined populations and rate estimates for microzooplankton grazing impacts on each phytoplankton component. The natural water column, marked by the drifting array, will be sampled again (all variables as above) around sunset and when the array is recovered and the experiments terminated ($t = 24$ h).

An additional suite of related experiments will be set up and incubated on shipboard. These include: 3) **^3H -thymidine and ^{14}C -leucine uptake experiments** – time series of short (60-min) incubations to assess production rates of bacteria; 4) **Full dilution experiments** (16 bottles: 5

replicated treatments and controls) for two light depths (mid-mixed layer, lower euphotic zone) to resolve grazing impacts as a function of grazer biomass; 5) “**Grow-out**” incubations to evaluate the potential for Fe-limitation constraints on net rates of phytoplankton growth and biomass accumulation; and incubation experiments to quantify 6) **Biomass-specific rates of mesozooplankton grazing** on major phytoplankton (and microzooplankton) groups and size classes. To put these grazing estimates into context (i.e., mesozooplankton community grazing impacts on the ambient micro-plankton assemblage) and to determine how the vertical distributions of sentinel species respond to physical structure of the water column, depth distributions of zooplankton abundance and biomass will be sampled with a Laser Optical Plankton Counter (LOPC) and a Multiple Opening-Closing Net & Environmental Sensing System (MOCNESS). As described in more detail in Field Methods (below), shipboard experimental studies of sentinel species will also be done as time allows on these cruises, focusing initially on egg production rates, ecological determinants of reproductive potential and sensitivities to altered system conditions.

Process Cruise Data and Relationships: EP cruises will provide a tightly coupled suite of related stock and process measurements to elucidate the response “trajectories” (i.e., net daily changes) of the plankton community under a broad range of initial conditions, and to parameterize and test models of system dynamics. For each phytoplankton group defined by pigments or size class, we will have instantaneous growth rates as a function of temperature, nutrients and light level, and their grazing loss rates as a function of microzooplankton biomass (total or by size class; e.g., nano-grazers feeding on picophytoplankton) and as function of mesozooplankton biomass. The latter may be useful in reconstructing retrospective grazing fields from historical assessments of CalCOFI zooplankton, and will likely also be important in explaining observed differences between community net rates of change in bottle incubations versus those from initial and final (24h, drift array) sampling of the ambient community. Export fluxes will not be measured directly, but can be constrained by the 1) differences between measured growth and losses, or 2) the combination of ^{14}C production estimates and observed net changes in bulk particulate (POC, PON) and organic (DOC, DON) measurements. Bulk nutrient uptake rates may be inferred from growth and production estimates and net nutrient changes, and their kinetics from an extensive literature. Many related measurements of this type are not feasible given programmatic budget constraints, but we would encourage cruise participation by colleagues with expertise in measuring parameters of mutual interest, particularly nutrient (N, Si) uptake and remineralization rates, particle aggregation mechanisms and export fluxes.

Time-Series Studies

Rather than initiate an independent LTER Time-Series program, we will capitalize on on-going efforts by adding select measurements relating to our long-term research objectives. In addition to the obvious economies of more closely coordinating various sampling programs, we will benefit in particular from the broad spatial scope of the CalCOFI survey area and the great wealth of long-term data and biological samples from it. These provide an immediate historical context for new observations. We break the discussion below into measurements made on a more-or-less continuous basis *versus* the quarterly CalCOFI cruises.

Continuous Measurements

Scripps Pier. Temperature has been measured at the SIO pier since 1916, and other properties for varying lengths of time. Present measurements are made electronically, with appropriate calibration samples. Conductivity, temperature (SST), pressure, Chl a fluorescence, light transmittance and beam attenuation coefficient are recorded at 4-min intervals. Major changes in SST at the SIO pier are highly correlated within the CalCOFI domain, and also the larger NE Pacific, especially in winter (McGowan et al. 1998).

Ocean Institute (OI). our Education Outreach partner in Dana Point, makes ~150 student cruises per year on the 70-ft *R/V Sea Explorer* to an oceanographic station in close proximity to CalCOFI station 90.28. OI will conduct CTD casts and analyze samples for total phytoplankton biomass (as Chl a) to help us assess the propagation of Kelvin waves (e.g., during the onset of El Niño) and to engage students directly in this research project.

Southern California Coastal Ocean Observing System (SCCOOS) is a new consortium of 11 universities and laboratories in the S. California Bight region. SCCOOS will integrate data from various local, state and federal coastal observing systems to serve the needs of management agencies. Many of the observation sites within our LTER region will provide essentially continuous data streams of benefit for resolving high-frequency ocean responses. The measurement localities include CODAR sites for coastal winds and the NDBC (National Data Buoy Center) buoys, which typically measure surface air and sea temperature, winds and wave conditions; many measure incident solar radiation and most have Acoustic Doppler Current Profilers (ADCP) for current velocities. Bio-optical and other biologically relevant sensors have been proposed for a number of new sites.

Satellite Remote Sensing: Merged data from multiple satellites allows nearly complete coverage of our area based on weekly composites. These semi-continuous surface data will have sufficient frequency for us to quantify the transitions between system states and to study episodic changes in ecological structure in relation to physical variables such as satellite-derived winds, SST, and sea-level anomalies that we hypothesize are related to the intrinsic forcing mechanisms of the system. The MODIS global data set is now available at 1-km resolution within 24 h. These data will be used to explore details of spatial and temporal heterogeneity related to sample aliasing of classical oceanographic sampling grids such as CalCOFI. Certainly, interannual perturbations like El Niño/La Niña and seasonal transitions are easily characterized (Thomas & Strub; 1989; Thomas, 1999; Thomas et al., 1994; Kahru & Mitchell, 2000; 2001; 2002). Using high-spatial resolution data sets now available from multiple satellites, short-term events such as wind-driven upwelling plumes and mesoscale eddies can be monitored as well.

We will use the chlorophyll biomass, community structure (HPLC, microscopy) and primary production data from CalCOFI and LTER Process cruises to validate algorithms or to modify parameterizations to ensure more accurate regional retrievals as we have done already for Chl a and colored dissolved organic matter (CDOM) (Kahru & Mitchell 1999, 2001). We will routinely compute Chl a , CDOM, POC, particle size distributions, primary production and export production. At least two times per year we will re-process the time-series as satellite calibrations are updated, or algorithms are improved over time. Satellite data collected prior to and during cruises will be utilized to specify the system's structure, improving our ability to sample the potentially important, but relatively rare, extremes and to better understand how to extrapolate detailed ship observations to the system scale.

Images of surface Chl a and SST at 1-km resolution will define trajectories and boundaries of plumes, eddies and major water masses with different trophic structure. Such information will be used in real-time during planning and execution of the Process cruises. In YEARS 1-3, we will improve and verify the accuracy of satellite retrievals of Chl a , POC, CDOM, primary production and particle size distributions. The uncertainties of satellite estimates will be quantified relative to ship observations and incorporated into strategies to constrain the developing process models and facilitate data assimilation in YEARS 4-6. The temporal and spatial coverage of the satellite data will be essential in the YEARS 4-6 to assess the fidelity of the coupled bio-physical data assimilation model.

Quarterly Augmented CalCOFI Cruises

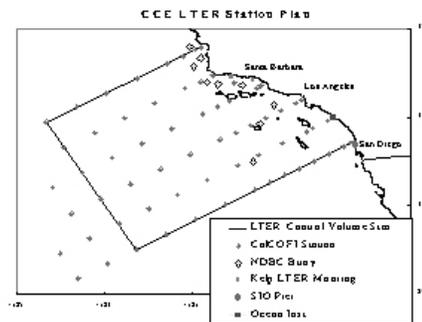
CalCOFI cruises sample a grid of 66 stations (Fig. 22) four times per year. CTD sensors provide basic depth profiles of pressure, temperature, conductivity, oxygen, Chl a fluorescence, 660 nm transmission and PAR at each station. In addition, rosette bottle samples are collected from 20 depths (or to the bottom) for discrete analyses of salinity, oxygen and most major nutrients (PO $_4$, SiO $_3$, NO $_3$, NO $_2$). Chl a is determined fluorometrically from the upper 14 depths, and primary production is estimated daily by 14 C uptake in simulated *in situ* incubations at six light levels. Large zooplankton are sampled with oblique tows from 210 m to the surface using a 505- μ m mesh net. NOAA fishery scientists from the Southwest Fisheries Science Center (SWFSC) have extensively investigated fish stocks and their recruitment dynamics in the CalCOFI sampling region. Under separate funding, the Point Reyes Bird Observatory has also censused seabirds and cetaceans on cruises since 1987. Detailed methodologies for CalCOFI measurements are described in CalCOFI data reports (e.g. Scripps Institution of Oceanography 2002) and can be accessed on line at <http://www.calcofi.org/newhome/index.htm>.

CalCOFI's historical focus on large zooplankton and fisheries provides insufficient data support for LTER Process and Modeling interests in lower trophic level biota. We, therefore, propose to augment quarterly sample collections with a basic suite of relevant measurements (Table 1).

Central to the augmented measurements are those defining the stocks and structure of the "microplankton" community (broadly, all organisms <200 μ m). Flow cytometry (FCM), taxon-specific pigments (HPLC) and microscopy complement one another in representing the various functional, size and taxonomic components. FCM analyses allow high-precision enumeration of heterotrophic and photosynthetic bacteria and pico-eukaryotic phytoplankton. HPLC-determined accessory pigments provide class-specific differentiation of phytoplankton taxa.

Microscopical/imaging techniques (epifluorescence, inverted and FloCAM) are essential for identifying changes in the dominant species of autotrophs, for enumerating heterotrophic (non-pigmented) populations, and for the accurate determination of mean cell sizes and biovolumes. These parameters will be sampled at all stations in the mixed-layer (surface maps), and at selected stations to resolve depth distributions. The same variables are also used in experimental

Fig. 22. LTER station plan, indicating the LTER control volume stations, existing CalCOFI stations, NDBC buoys, the Santa Barbara kelp forest LTER moorings, the SIO pier time series location, and the Ocean Institute sampling location near Dana Pt.



assessments of phytoplankton growth rates and zooplankton grazing impacts (Process Studies), and together they will allow for substantial flexibility in structuring ecosystem models based on size or functional groups. In addition, present assessments of mesozooplankton biomass and vertical distributions using the Optical Particle Counter (to about >250- μm equivalent spherical diameter) will be broadened, with the use of the Laser Optical Particle Counter, to include animals down to about 70 μm .

Table 1. CalCOFI time-series measurements. Black font = current; Red = proposed LTER parameter or method (details below).

<u>Parameter</u>	<u>Investigator</u>	<u>Method</u>
Upper ocean currents	Chereskin	ADCP, data analyses
Temperature, salinity, Chl <i>a</i> fluorescence	CalCOFI	CTD w/ fluorometer
Irradiance (<i>in situ</i> profiles & daily PAR)	CalCOFI	PAR meters
Light transmission @ 660 nm	CalCOFI	transmissometer
Oxygen	CalCOFI	CTD, auto-Winkler
Nutrients (N, P, Si) - ammonium	CalCOFI	Auto analyzer
Iron concentration	Barbeau	FeLume flow injection
Sea surface pCO ₂ *	CalCOFI	IR absorbance
Particulate C&N	Aluwihari	dry combustion
Dissolved organics (DOC, DON)	Aluwihari	combustion
Primary production **	CalCOFI	¹⁴ C-uptake - POC, DOC
Chl <i>a</i> concentration (extracted)	CalCOFI	Fluorometer
Taxon-specific pigments	Goericke	HPLC
Bacteria & picoautotrophs	Landry	Flow-cytometry
Nano- & microplankton	Landry/Venrick	Microscopy, FloCAM
Mesozooplankton, optical size classes	Checkley	OPC, LOPC
Mesozooplankton, sentinel species	Ohman	Microscopy, ZOOSCAN
Nekton	SWFSC	fish egg counts, trawls

* Measurement to be added 1/04 through collaboration with MBARI.

** Measurement likely to be augmented by bio-optical approaches with NOAA funding.

Additional elemental measurements are also included in the augmented CalCOFI measurements. Iron (Fe) is demonstrably important as a control of biomass accumulation within our study region (King & Barbeau 2004), and ammonium is a key indicator of N remineralization activity. Particulate C&N measurements constrain the mean C:N ratio of small particulates and, by difference relative to measured living biomass, the biomass of suspended detritus. Dissolved organics (DOC, DON) have many links in microbial food web interactions, and, because of their large pool sizes, are essential for flux calculations for “Control Volumes”.

Lastly, upper ocean currents are routinely measured by ADCP on CalCOFI cruises, but the records have generally not been processed. To better resolve flow fields in the sampling region, backlogged and on-going ADCP data will be processed to velocity vectors at 5-km resolution under the direction of T. Chereskin.

Field Study Methods

Upper-ocean currents (ADCP): CalCOFI cruise vessels are equipped with narrowband 150 kHz ADCPs. Data processing will include correcting for transducer misalignment and mean heading biases (Pollard & Read 1989) and translating ship-relative currents to absolute currents using GPS position data. ADCP data are edited to remove bottom interference; the barotropic tide is estimated and removed using the OSU global tide model TPXO6.2 (Egbert et al. 1994). Resultant velocities are mapped by quasi-geostrophic streamfunction objective analysis (Chereskin & Trunnell 1996).

Iron: Trace metal clean techniques will be employed for all Fe sampling and analyses. Surface samples will be collected (Boyle et al. 1994) at ~30 stations per cruise, with highest frequency sampling at shoreward stations. Depth profiles at select stations will be obtained using 12-L teflon-lined, Go-Flo bottles on a nylon hydro line. After sampling Go-Flos will be pressurized using filtered UHP nitrogen gas, and seawater for analysis will be dispensed via acid-clean Teflon tubing directly into a Class-100 laminar flow clean bench. Total dissolved (0.4- μm filtered, $\text{pH}<2$) and dissolvable (unfiltered, $\text{pH}<2$) FeII will be determined to sub-nanomolar concentrations with a Waterville Analytical FeLume flow injection system based on luminol chemiluminescence (e.g., Emmenegger et al. 2001, Croot & Laan 2002).

Dissolved Organic Carbon and Nitrogen: Seawater samples (40 mL) will be drawn from the CTD rosette into combusted glass vials with acid-washed Teflon caps, acidified with 85% phosphoric acid and stored at room temperature (Aluwihare et al. 2002). Samples from Time-Series cruises will be processed in the shore-based laboratory with a Shimadzu TOC-V analyzer with a DON upgrade. This instrument will be fitted for shipboard analyses on the Process cruises, allowing real-time measurements of DOC and DON to follow DOM dynamics of natural blooms or shipboard incubations (Boyle et al. 1994).

Particulate Carbon and Nitrogen will be measured for 1-L samples, filtered onto precombusted glass-fiber filters, dried for 48 h at 60°C, and analyzed by high-temperature combustion (Perkin Elmer Model 2400 Elemental Analyzer) relative to standards and blanks.

Phytoplankton Pigments: Samples will be concentrated on GF/F or Nuclepore filters (total or sized-fractionated samples) and stored in liquid N₂. Pigments are extracted in acetone and analyzed by reverse-phase HPLC for major chlorophylls and taxon-specific carotenoids (Goericke & Repeta 1993). Chlorophyll contributions by the major phytoplankton groups are calculated from class-specific accessory pigments according to the primary and ancillary ratio approach of Goericke & Montoya (1998). In combination with microscopic analyses, group-specific carbon ratios (e.g., C_{diatom}:fucoxanthin) will be determined to assess pigment ratio variability as a function of nutrient concentration and light condition, and to evaluate pigment acclimation effects in experimental incubations for growth and grazing rates.

Microbial Community Abundance and Biomass, including auto- and heterotrophic bacteria and protists, will be determined from flow cytometric (FCM) and microscopical methods as used in the Hawaii Ocean Time-series Program. Picoplankton samples (2 ml) will be preserved (paraformaldehyde, 0.5% final) and frozen in liquid N₂. At the SOEST Flow Cytometry Facility (Univ. Hawaii), these samples will be stained with Hoescht 33342 (Monger & Landry 1993) and analyzed with a Beckman-Coulter EPICS Altra flow cytometer with dual lasers. This system distinguishes populations of *Prochlorococcus*, *Synechococcus*, heterotrophic prokaryotes, picoeukaryotic algae by differences in light scatter and fluorescence emission. All samples are spiked with fluorescent beads to normalize fluorescence and scattering properties.

Samples for nanoplankton analyses (20-50 mL) will be preserved (2 mL, 10% paraformaldehyde), stained with the fluorochromes proflavin (25 μL , 0.033% w/v) and DAPI (50 $\mu\text{g mL}^{-1}$), filtered onto 0.8- μm black polycarbonate filters, and mounted onto glass slides. These slides will be analyzed by size class and major taxon (diatoms, dinoflagellates, etc.) with a Zeiss Axiovert 200 microscope equipped with a fully motorized stage and Apotome imaging workstation for automated processing, 3-D reconstruction and extended-field focus.

Microplankton samples (500 mL; glutaraldehyde and acid Lugols preserved) will be enumerated and sized with the Zeiss Axiovert system (inverted DIC mode) or with a newly acquired Flow Cytometer And Microscope (FlowCAM) system (Sieracki et al. 1998). Particle silhouettes are acquired in the FlowCAM's optical sensing volume using frame-grabbing technology. Imaging software then estimates equivalent spherical diameters (ESD) and normalized particle size distributions (log ESD vs. log size; ~1000 particles/analysis). For each plankton group or size category, measured biovolumes will be converted to cellular C using the equations of Verity et al. (1992) and Menden-Deur & Lessard (2000).

Mesozooplankton Abundance and Biomass will be routinely sampled from 0-210 m with oblique tows of flow-metered 202- μm mesh bongo net with a mouth-mounted LOPC (Herman et al. 2001).

Determination of biomass will be done on formalin-preserved samples using the ZOOSCAN (Grosjean et al. 2004), which rapidly scans, digitally images and classifies animals >200- μm by size and shape (Grosjean et al. 2004). Size-based estimates of biomass will be obtained using appropriate length-mass and length-C relationships.

On PE Cruises, vertically stratified samples will be taken with an 1 m²-MOCNESS (Wiebe et al. 1985), with 333- μm mesh nets to assess changes in the vertical habitat of sentinel zooplankton species in relation to the altered vertical structure of the water column (pycnocline, nitracline, etc.) and predator fields as inferred indirectly from shipboard bioacoustic measurements. Replicated day/night tows will be done to 500-m depth, with higher vertical resolution in the upper 100 m. Depth profiles of selected taxa will be assessed in at least four CCE subregions during each Process cruise, through laboratory-based microscopical analyses.

Bacterial Production will be determined by ³H-thymidine (nucleic acid synthesis; Fuhrman & Azam 1982) and -leucine (protein synthesis, Simon & Azam 1989, Smith et al. 1992) uptake methods by an SIO student trained by LTER Associate F. Azam. For thymidine, replicate samples (and formalin-killed controls) are terminated with formalin at 0 and 60 min. Leucine experiments involve 6-min incubations of triplicate filtered and unfiltered seawater samples and analytical blanks obtained by adding TCA prior to leucine. For both methods, incubated samples will be centrifuged and washed as described by Smith & Azam (1992).

Grow-out Experiments will be conducted to assess potential limitation of phytoplankton standing stocks by iron (e.g., Hutchins & Bruland 1998; Hutchins et al. 1998). Near-surface (5-10 m) waters for incubation studies will be collected with Go-Flo bottles or an all-Teflon surface pumping system using trace metal clean techniques, and dispensed under the laminar flow hood into acid-cleaned 2.7-L polycarbonate control and +Fe incubation bottles. Iron will be added as an inorganic stock solution to a final concentration of 2.5-10 nM. Control and +Fe experimental bottles will be incubated for 1-4 days in a spectrally-corrected, flow-through deck incubator at 30-50% of incident light to mimic conditions in the mixed layer. Samples will be taken daily for size-fractionated (0.2 & 8.0 μm) total Chl *a* and taxon-specific pigments, nutrients, POC/PON and phytoplankton cell counts.

Pigment Labeling Experiments will be used to measure rates of primary production, C:Chl *a* ratios and phytoplankton community and taxon-specific growth rates (Redalje & Laws 1981, Gieskes & Kraay 1989, Goericke & Welschmeyer 1993a,b). Experimental water will be collected from 8 light depths in the euphotic zone before sunrise with 30-L Go-Flo bottles, and 8-L polycarbonate bottles will be filled using trace metal-clean procedures (Fitzwater et al. 1982). The bottles will be spiked with ¹⁴C-bicarbonate (250 μCi) at first light and incubated *in situ* on a drift line for 24 h. Instantaneous growth rates (μ , d⁻¹) are determined from the specific ¹⁴C-activity of Chl *a* or taxon-specific carotenoids using functions which relate pigment-specific activities to μ (Welschmeyer & Lorenzen 1984). Phytoplankton C:Chl *a* ratios are determined from rates of carbon fixation and community (Chl *a*) growth.

Microzooplankton Grazing will be measured with dilution experiments (Landry & Hassett 1982). Full 5-treatment experiments (replicated bottles with D = 100, 80, 60, 40 and 20% natural seawater) will be run for two standard light depths (mixed layer and lower euphotic zone) and incubated in seawater-cooled incubators for the natural 24-h photocycle (Landry et al., 1995a,b, 2000, 2003). Two-treatment experiments consisting of D = 20% and 100% natural seawater (e.g., Landry et al. 1984, Brown et al. 1999) will be incubated for each depth on the *in situ* array. Micro-herbivore density, hence grazing impact, is reduced by dilution (D), allowing grazing mortality rates (m) to be calculated from treatment differences in net ($k = \mu - D \cdot m$) measured rates of phytoplankton growth (regression analysis for full experiments or 2 equations, 2 unknowns). Rate estimates (μ and m) will be determined for the mean community (Chl *a*) and component groups (FCM and HPLC pigments). Disappearance rates of fluorescently labelled tracer cells are used to assess non-linearities rate determinations (Landry et al. 1995b).

Mesozooplankton grazing: Mixed zooplankton samples will be collected with gentle nighttime tows with a 202- μm net with large volume cod end and carefully sieved into $> 505\mu\text{m}$ and 202-505 μm fractions. Grazing incubations will be done in 30-liter flow-through salp-o-stats designed by M. Landry (circulating flow chamber inside a in a separately controlled seawater bath), using natural seawater as the prey suspension. Incubations will be carried out on a natural day/night cycle, and the difference between phytoplankton concentrations in the inflow and outflow will be used to assess total biomass-specific ingestion rates (Chl *a*, PC:Chl estimates), as well as relative grazing impacts on major phytoplankton taxa and protozoa (HPLC, FloCAM). Flow rates will be adjusted to measureable net changes in phytoplankton concentrations (continuous fluorometry). All experimental and control treatments will be replicated, and the mesozooplankton biomass in each incubation determined by filtration and CN combustion in an elemental analyzer.

Shipboard studies on sentinel species: Initial experiments will focus on the dominant species of euphausiids in this part of the California Current, *Nyctiphanes simplex* and *Euphausia pacifica*, the copepod *Calanus pacificus*, and salps (*Cyclosalpa bakeri*, *C. affinis*, *Pegea socia*, and *Salpa maxima*), as found opportunistically. Given the demands of other aspects of the study, rates of egg production will be the primary response variable measured. This is relatively straightforward for *Calanus* (e.g., Mullin 1993, 1997, Ohman et al. 1998, Runge & Rolf 2000), but requires longer incubations and careful consideration of size-fecundity relationships for euphausiids. *N. simplex* carry eggs in attached egg masses, while *E. pacifica* are broadcasters, so measurement protocols will differ. For *N. simplex*, egg hatching rate will be determined as a function of temperature, and these rates applied to the egg abundances determined from nocturnally-collected females at different sites, to infer reproductive responses to diverse ocean conditions. Direct incubations will be carried out with *E. pacifica* females, to assess egg release rates into the effluent of the salp-o-stats over the course of a week. The same individuals will be maintained alive and transported to a different region of the CCS where the prey suspensions are markedly different, to assess the acclimated egg production rates on the new assemblage, again for approximately 1 week. Such “transplant experiments” will be done several times during each PE cruise. This approach will enable us to use egg production rates as a measure of the animals’ demographic response to spatial differences in the composition and structure of the lower elements in the food web. Salp responses, where and when possible to assess, will consist of quick-freezing animals and analyzing dissected gut contents by fluorometry, and application of egestion rates from the literature (e.g., Madin & Deibel 1998) to approximate ingestion rates.

Modeling Studies

The modeling part of this LTER both supports and builds upon the proposed data collection and analyses. Modeling will provide: 1) a mathematical structure for quantifying the dynamics underlying the observations; 2) a synoptic environmental context (physical, biological, chemical) for the point observations, and a means for dynamic interpolation between observations in space and time; 3) a platform for hypothesis testing through numerical experiments and process models; 4) guidance for optimizing the sampling program.

We will approach these goals incrementally. Initially (YEARS 1-3), our efforts will be put toward 1) the collation, synthesis, and analysis of archived data, 2) the development of planktonic ecosystem models capable of reproducing the changes observed in the ecosystem during El Niño/non-El Niño transitions, and 3) the coupling of the ecosystem models to one-dimensional (1D) and 2D physical models. In the subsequent 3 years, the biological models will be coupled to the extant 3D physical model of the region. This model will be used to assimilate and forecast the data, and will also form the basis of inverse models that will be used to gain insight into the dynamics underlying the observations.

Model Development

A central issue in developing an ecosystem model is choosing the type and degree of aggregation: how many state variables will be included in the model, and what will these state variables represent? The rich data set generated during this program will include measurements of the biomasses (or biomass proxies) of a range of phytoplankton taxa (e.g., *Synechococcus*, *Prochlorococcus*, diatoms, dinoflagellates, prymnesiophytes, etc.), dissolved organic nitrogen (DON), particulate nitrogen, inorganic nitrogen, dissolved and particulate iron, microzooplankton, and mesozooplankton, as well as important rates: phytoplankton taxon-specific growth rates, the relationship of phytoplankton taxon-specific growth rates to inorganic nutrients and light, DON production rates, size-specific microzooplankton ingestion rates, bacterial production rates, primary production rates, and the production rates of dissolved organic carbon. To maximize our ability to incorporate these measurements into the models, and to be able to test and reject alternate models, we will aggregate our ecosystem models by phytoplankton taxon and size of zooplankton.

The state variables for our initial ecosystem model will include both the cyanobacteria *Synechococcus* and *Prochlorococcus*, diatoms, dinoflagellates, and “other” phytoplankton; nanozooplankton, microzooplankton, and mesozooplankton; heterotrophic bacteria; DON, nitrate, ammonium and detrital pools. Additional pools to be considered include silicate and iron. The models will be parameterized using literature and cruise data, and tested with independent data gathered during the Experimental Process Studies. The models must be capable of reproducing the observed or inferred changes in the food web during El Niño/non-El Niño transitions, as well as the “basic” state of the ecosystem.

The ecosystem models will be coupled to 1D (vertical) physical models to explore their response to changes in stratification (and subsequent changes in vertical nutrient fluxes), and changes in meteorological forcing. Coupling the model to 2D (cross-shore) physical models will allow exploration of the effects of meteorological forcing and stratification on cross-shore transport and ecosystem structure and dynamics. Changing the parameterization of the mesozooplankton will allow testing of the effects of altered predator fields on ecosystem dynamics. The ecosystem and physical/ecosystem models will thus serve to synthesize a diverse array of data, and provide a mechanism for diagnosing the underlying dynamics, testing hypotheses, and potentially making predictions.

In the future, we propose to develop detailed individual based models (IBM) for three sentinel species: *Euphausia pacifica*, *Nyctiphanes simplex* and *Calanus pacificus*. These models would be formulated and parameterized with archived data, and data gathered during the Experimental Process Studies. The IBMs will allow testing of hypotheses specific to particular species responses to environmental forcing. A 3D physical model of the California Current, which emphasizes circulation in the Southern California Bight, is currently operational. Di Lorenzo (2003) showed how the seasonal cycle of currents evolves from upwelling conditions in the spring to eddy-dominated flows in the fall. Di Lorenzo et al. (2004a) studied the mechanisms that caused the 1 °C warming of the California Current observed by CalCOFI over the past 50 years. In spite of increased upwelling-favorable winds (that would have cooled the ocean), warming by heat fluxes from the atmosphere capped the upwelling circulation by increasing the stability of the water column. This slowed down nutrient fluxes from depth to the surface photic zone. This may explain the observed decrease in zooplankton abundance over that time period and suggests that ecosystem productivity has decreased. We have also used the model to reproduce one-month-long hydrographic surveys of CalCOFI using techniques of data

assimilation (or model fitting). Miller et al. (2000) used an inverse method to fit the July 1997 cruise simply by adjusting the initial conditions of the model in a formal way. Di Lorenzo et al. (2004b) fit the February 1998 cruise and used the physical model to drive the 7-component ROMS ecosystem model. It matched well with both the SeaWiFS Chl *a* and CalCOFI *in situ* Chl *a* (Fig.

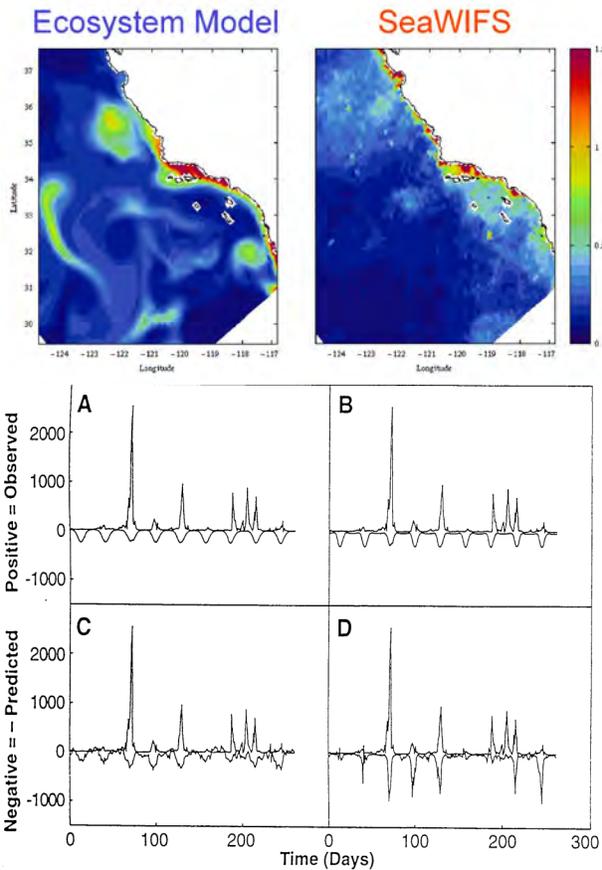


Fig. 23. Left panel: Surface Chl *a* from the coupled physical-ecosystem model of Di Lorenzo et al. (2003) in the Southern California Bight. Right panel: SeaWiFS remotely sensed surface Chl *a* patterns in the same region. The model reproduces the high pigment concentrations in cyclonic eddies, and the low concentrations seen in anticyclonic eddies.

Fig. 24. Predicted versus observed values for four physical models derived to explain episodic fluctuations in the larval supply of a common reef fish. Positive axis gives observed larval number; negative axis is (-1 X predicted value). The model building procedure involves exhaustively searching parallel time series of physical measurements, to find the best statistical model of each type (linear ARMA or nonlinear SIMPLEX). (A) optimal univariate linear (ARMA) model, using lunar phase lagged by 19 d. These fish spawn on the full moon, and the time to mature to the free-swimming larval stage is 10-19 d. (B) As in (A) but with a nonlinear model operating on lunar phase. (C) linear trivariate model. and (D) nonlinear trivariate model. The trivariate model included: (i) percent illumination lagged 19 d, (ii) cross shelf wind speed, and (iii) daily wind speed lagged 16 days. (Dixon & Sugihara 1999)

23) observed during this El Niño period of weak upwelling. Studies such as these help us to understand the physical balances and biological fluxes the control observed changes. However, the lack of additional biological data has left most of the model variables unconstrained.

The physical model is an eddy-resolving primitive equation generalized sigma-coordinate ocean circulation model called the Regional Ocean Modeling System (ROMS; Marchesiello et al. 2001). The northern, southern and western boundaries are treated as open boundaries using a modified Orlanski radiation scheme nudged to specified time-dependent temperature and salinity from CalCOFI climatology blended with Levitus. Realistic bathymetry is obtained from ETOPO-5, and a coastline is included via masking along the eastern boundary. The sigma layers have increased resolution in the surface and bottom boundary layers. Vertical mixing is treated with a KPP scheme (Large et al. 1994), and horizontal mixing occurs in the highest enwavumbers implicitly within the upstream discretization scheme.

Modeling Approaches

Nonlinear analyses and biological model parameterization: Our first task in formulating and parameterizing the biological models will be to collate and synthesize appropriate data from the literature and archives. In parallel with development of the ecosystem and IBM models, these

data will be analyzed using nonlinear, nonparametric techniques to attempt to determine model structures from the time-series observations. These techniques can help us quantify the degree of nonlinearity of the dynamics that generated our observations, and how many dimensions are needed to describe the observed system. Since the nonlinearity and dimensionality can change depending on the spatial and temporal resolution of sampling and the level of aggregation of the data, these analyses should help us design the ecosystem models: choosing the appropriate level of aggregation (how many boxes, and what is in them), and the appropriate level of model complexity to reproduce the data (what is the character of the functional responses linking the model's variables). One approach is to perform nonlinear analyses of the model outputs to see if there are simpler analogs (or if more complex models are required).

Process models and nonlinear analysis techniques will be used to test and refine the models, to test specific hypotheses, and to explore and quantify the dynamics of the community responses to environmental perturbations. Process models will be simplified versions of the full models, including only the dynamics felt to dominate in generating the signal being explored. For instance, to explore responses of the ecosystem to changing stratification, it may not be necessary to use a full 3D model, but rather a simple 1D model with a suitable turbulence scheme.

Nonlinear analysis techniques (Fig. 24) are useful tools for exploring the dynamics of time series and spatially resolved data. A good example of the application of the technique was given by Dixon & Sugihara (1999), in which it was shown that a time series of episodic larval fish recruitment could be well described by nonlinear combinations of unrelated forcings: lunar phase, turbulence and wind direction. Nonlinearity is seen as the product of these three conditions ((i) a full moon with (ii) moderate turbulence 16-19 days ago, and (iii) moderate onshore winds today), with peaks in abundance occurring as "the perfect storm" – the unusual co-occurrence of these three factors.

These and other nonlinear analysis techniques will be applied to archived data from the CalCOFI program, data gathered during this LTER, and model output. These approaches should help us understand the dynamics leading to abrupt changes in the ecosystem and sentinel species on interannual time scales.

Forecast/assimilation: Process cruises data will be merged with other data (CalCOFI cruises, satellite altimetry/SeaWiFS, other remote sensing/CODAR) in the physical and biological models. The disparate data types will be mapped onto regular grids in real time using data synthesis techniques. These techniques can include both relatively simple statistical methods, like optimal interpolation, and relatively sophisticated data assimilation procedures with dynamic ocean models, like 4D variational assimilation (4DVAR) and representer methods. Both of these modern fitting techniques are nearing completion with the ROMS model under separate funding. We will produce 4DVAR strong constraints data assimilation fits of the (month-long) time periods of the LTER Process Studies. These fits will produce optimal initial conditions, boundary conditions, and surface forcing functions over the time period of the data sampling.

The data assimilation fits will provide plausible dynamical linkages between local observations and large-scale variations within the CCE. They are aimed at producing estimates of variability in regions with no data, and within the model structure they will allow an optimal presentation of error estimates and a diagnosis of dynamically adjusted fields that can aid in the identification of where better or more data are needed. Although a far-off goal, dynamical mappings will also allow the development of forecasting capabilities in the mature stages of the LTER effort.

Long-term regional simulations: To put LTER results into context with the past observations of CalCOFI, a 50+ year (1950-present) simulation of physical-biological variability of the CCE will be produced with an eddy-resolving ocean model at 5-10 km resolution with 20 vertical layers. This will expand the interpretation of CalCOFI from the classic time-aliased view to the modern time-evolving view of physical balances and biogeochemical response to upwelling, eddy formation and variable external forcing. Our previous work (Di Lorenzo et al. 2003) revealed the thermodynamics of the long-term warming trend in the CCS (Roemmich & McGowan 1994) despite an *increase* in upwelling favorable winds over the last 50 years. Large-scale surface heat flux forcing, combined with southward advection of heat by the CC, formed a stable upper-ocean stratification field that does not allow as much nutrient flux from depth to reach the photic zone (Di Lorenzo et al., 2003; McGowan et al. 2003).

We will extend these simulations through the time interval of the LTER observations. Forcing will come from the wind stresses, heat fluxes and fresh-water fluxes of the NCEP/NCAR re-analysis products downscaled to 10-km resolution by Kanamitsu (ECPC) as part of a separate project. Boundary conditions (following Di Lorenzo et al. 2003) are provided by time-dependent and z-dependent estimates of CalCOFI domain averages of temperature and salinity (blended with Levitus climatology at depth greater than 600 m where no data exists). These simulations do not mimic the exact timing and individual appearance of mesoscale eddies, but allow this intrinsic variability to play a fundamental role in influencing vertical, along-shore, and cross-shelf fluxes of nutrients and Lagrangian particle transports.

Inverse models are powerful tools for understanding the dynamics of a set of observations. An example is the adjoint method, in which a cost function is defined to quantify the fit between a model output and data. A model can be initialized with one data set, and then run forward in time and compared to a second data set. The model can then be run backward in time, and the adjoint and cost function will dictate the model changes needed to achieve better agreement with the data. Successive iterations of this method – minimizing the cost function – allow the data to give a best version of the model. In this way, within constraints of the cost function chosen, a best-fit model architecture and parameterization can be obtained, with a statistically quantifiable confidence in the ability of the model to mimic the “apparent” dynamics of the observed system. This adjoint method has been applied in several oceanic systems with considerable success as a fitting method (McGillicuddy & Bucklin 2002, Spitz et al. 1998), and we propose to further develop and apply the technique to the data collected during this LTER program.

The adjoint of a 7-compartment ecosystem model (Moisan et al. 1996) is currently nearly completed under separate funding. The physical model fits will provide the forcing for the biogeochemical model. We will use the adjoint of the biogeochemical model to optimize initial conditions, boundary conditions, and also key uncertain model parameters (e.g., the least known or the most sensitive) to improve the fit to all available biogeochemical data in the fitting period.

Control volume calculations: One motivation for the LTER/CalCOFI augmentation sampling design is that it will allow us to accurately estimate net fluxes of properties such as heat, salt, nutrients, oxygen and chlorophyll through the 3D box defined by the stations and the coast. If there is little vertical transport at the deepest level of sampling (500 m), which is likely the case in the long-term mean, the defined box represents a control volume (Fig. 25) within which the Ekman and geostrophic transports will theoretically balance. This formulation was developed and tested by Roemmich (1989), and Bograd et al. (2001) refined the method and described interannual variability in the property fluxes.

The net flux of a given property, C , into the control volume refers to the combination of its geostrophic and Ekman components, so that its time-mean conservation equation can be written as:

$$\int_{-500}^0 \int_{l_i}^{l_f} C v_g dldz + \int_{l_i}^{l_f} C_{z=0} \vec{T}_{Ek} \cdot \hat{n} dl = Q$$

where v_g is the geostrophic velocity normal to the box, referenced to 500 m, l is the along-box coordinate, T_{Ek} is the Ekman transport, Q represents the strength of any sources or sinks of the property within the box, and mass is assumed to be conserved for each box occupation. For nitrogen fluxes, for instance, C might be the nitrate concentration, and Q is equivalent to the net amount of nitrate created/lost within the box by biological or chemical processes or transported by horizontal and vertical currents. Estimates of mean primary production in the box can be inferred from the derived net nutrient (nitrate, phosphate) fluxes. Both Roemmich (1989) and Bograd et al. (2001) found a close balance between geostrophic convergence and Ekman divergence in the seasonal and long-term means. This speaks to the validity of this simple box model for monitoring changes in geostrophic circulation and Ekman transport and for deriving reasonable estimates of property flux convergences and primary production. Dedicated, near-synoptic sampling of the box perimeter will permit more accurate estimation of Ekman and geostrophic transports; the proposed measurements of dissolved organic matter (DON, DOP, DOC), and particulate organic nitrogen will allow the nutrient budgets to be closed, greatly improving estimates of net primary production.

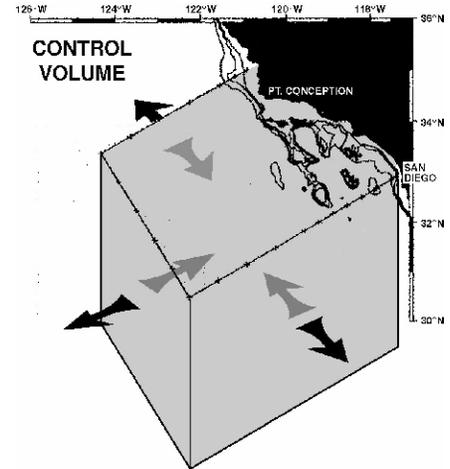


Fig. 25. Three-dimensional Control Volume defined around the open boundaries of our study site (after Bograd et al. 2001).

Regionalization and Comparative Studies

Linkages to other LTER sites

We have great interest in comparative studies with a number of existing LTER sites and anticipate many more as we become better acquainted with others in the network. An immediate and mutually beneficial interaction will be with the **Santa Barbara kelp forest** site, which is within the spatial boundaries of our pelagic coastal ocean site. That site seeks, in part, to understand the influences of the nearshore ocean on kelp ecology. An important consequence of El Niño on the kelp canopy, in addition to the effects of Niño-associated winter storms, is the decreased availability of nutrients through depression of the nutricline. We will have a rich empirical data set, and eventually excellent models, that will help in understanding time/space variability in nutrient supply during Niño passage. In December 2003, we had preliminary in-person discussions on this subject and look forward to providing a larger scale perspective for interpreting locally measured processes affecting kelp forests in the coastal ocean.

The **Palmer Station** LTER, with its research on krill population dynamics, is another partner with whom we have communicated. Euphausiids (krill) include some of the primary sentinel species that we will focus upon in the CCE LTER. Comparative studies between the congeners *Euphausia superba* and *E. pacifica* with respect to life histories, demography, and mechanisms of response to climate forcing will be of principal interest.

We anticipate comparisons with the **North Temperate Lakes** site, with respect to the roles of predators, nutrient fluxes and disturbance in regulating community structure. As alluded to earlier, the scaling issue for pelagic environments and the relative magnitudes of biotic vs. physical forcing in pelagic lacustrine and pelagic marine systems are open questions. We further expect to interact with colleagues on the themes of alternate stable states, the consequences of ENSO-related forcing, and other topics.

We also anticipate involvement in the LTER **Microbial Observatories and Modeling** initiatives in the very near term.

Linkages to other Programs

We expect to partner with, and benefit from, a number of research programs either currently in existence or under development. A proposal recently submitted to NOAA would develop **SCCOOS**, the *Southern California Coastal Ocean Observing System*, which would link a number of observational oceanography programs in the nearshore zone of the Southern California Bight and provide a network of moorings, buoys, CODAR, glider, and beach sampling programs for high-frequency measurements of direct relevance to this LTER site. We have had discussion with Russ Davis concerning the addition of bio-optical and nutrient sensors to his innovative, autonomous ocean gliders. This could become a new long-term observational tool in the near term. The deep-sea particle flux and benthic community studies of Ken Smith (e.g., Smith et al. 2001) provide a connection to the benthos. We have reason to believe that variations in such particle fluxes are directly related to the plankton community structure in the overlying water column. Ron Burton's lab is currently developing DNA oligonucleotide probes for estimating species-specific abundances of diverse marine micro- and nanoplankton in seawater samples. Such probes would be a useful, rapid approach for assessing protist abundances and growth rates in our site. Ongoing paleoceanographic studies from the sediments of the anoxic Santa Barbara and Santa Monica Basins, both within our LTER domain, are invaluable in placing contemporary climate variation in the context of historic ocean variability (e.g., Zhao et al. 2000, Friddell et al. 2003, Field 2004).

Personnel, Project Management and Site Governance

There are two levels of involvement in the CCE LTER site: co-PI and Associate. Co-PI's will participate fully in the research activities, decision-making and management of this LTER site, as well as connections within the larger LTER network. The Associates conduct related research that directly benefit the LTER program and vice versa. In addition to the brief listing of co-PI's and Associates (Table 2), terse Biographical Sketches for each may be found in the Appendix. Both our Information Manager and Education and Outreach facilitators will be closely linked with all site activities. A considerable number of graduate students, postdoctoral investigators, and undergraduates will be actively involved in this site.

Scientific planning for this site will be by participatory, open discussions to which all co-PI's and Associates are welcome to contribute. In addition, an executive committee of four people has been formed consisting of the Lead PI (Ohman) and representatives from each of the following major elements of the science plan: Modeling (Franks), Experimental Studies (Landry), and Time Series Studies (Goericke). The representative from each major program element will serve on a rotating basis. Authority for allocation of resources will rest with the Executive Committee, upon consultation with the community of participants.

Beyond these site participants, we also will create an external 3-member CCE Advisory Board, which is intended to provide evaluation and constructive criticism of our aspects of our site's activities and objectives on an annual basis. The external advisory board will be drawn from institutions outside of SIO and will include leading ecologists, at least one representative from an experienced LTER site, and at least one person from outside the marine sciences.

We will hold an annual meeting where all CCE site participants (students, technical staff, Associates, PI's, Education and Outreach partners, and external Advisory Board) will meet to review the progress made in the previous year, discuss objectives for the forthcoming year, and address concerns related both to site science and site management.

Table 2. Participants in the CCE LTER site.

<u>Name</u>	<u>Role</u>	<u>Institution</u>	<u>Interests</u>
Mark Ohman	Lead PI	SIO	Mesozooplankton Ecology
Lahini 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 and 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
David Hyrenbach	Associate	Duke/PRBO	Seabird Ecology
Cheryl Peach &	Associate	BAS &	Education and Outreach planning
Sharon Franks	Associate	CA COSEE	Education and Outreach planning
Brian Palenik	Associate	SIO	Microbial Diversity
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SIO= Scripps Institution of Oceanography, PFEL=Pacific Fisheries Environmental Laboratory, Georgia T=Georgia Institute of Technology, Duke = Duke University, PRBO = Pt. Reyes Bird Observatory, BAS = Birch Aquarium at Scripps, CA COSEE= California Center for Ocean Sciences Education Excellence, SWFSC=Southwest Fisheries Science Center/U.S. National Marine Fisheries Service

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Facilities, Equipment and Other Resources

Each of the PI's has extensive experience in making the measurements they have proposed. Appropriate equipment for collecting and analyzing the samples exists in the PI's laboratory. Nutrient analyses will be done by autoanalyzer at the Ocean Data Facility at SIO. Flow cytometric analyses will be made at the SOEST FCM facility at the University of Hawaii. Other than the minimal computer upgrades requested during the course of this program and a new dedicated server for Information Management, the computer facilities at SIO and those available within each PI's lab are sufficient for the proposed modeling, data analysis, and information management. The shipboard studies will be performed on the R/V *Roger Revelle* or similar vessel, with supplementary support from the R/V *New Horizon* or R/V *David Star Jordan*, or similar vessel.

Education and Outreach: The three main partners – the Birch Aquarium at Scripps, the Ocean Institute, and Aquatic Adventures – each have facilities to accommodate and teach tens to hundreds of students at a time, and have extensive experience in program development to serve K-12 students. The Ocean Institute's vessel, R/V *Sea Explorer*, is equipped with a Sea Bird CTD/rosette system.

Data and Information Management for the California Current Ecosystem (CCE)

Data management (DM) for the CCE LTER will provide for both short-term PI needs and for long-term storage and access to the site's pelagic coastal ocean datasets, building upon contemporary understandings of infrastructure, open source community, and national metadata standards. The CCE data component basic tenets include: (1) data management as an integral part of the research program; (2) establishment of a centralized open source environment that plans for a diversity of computer platforms and tools among participants; (3) establishment of electronic communication systems available to all; (4) development of an electronic central database offering continuity, accessibility and extensibility for long-term data; (5) use of metadata for interoperability of databases and data reuse; and (6) recognition of the value of information environment design as a tool to facilitate information flow and collaborative science. The challenge is to create the processes that deliver a robust, powerful system that is low maintenance yet sustainable over time.

The data model includes participants responsible for preprocessing and contributing identified sampling groups of time-series, process, continuous, and derived/associated datasets that are physical, chemical, biological data taken using a variety of sampling methods: (1) point or integrated samples; (2) discrete and oblique profiles, (3) continuous vertical profiles, (4) continuous underway measurements and (5) images. Documentation and data storage will be organized through an electronic hub at the Integrative Oceanography Division (IOD) at Scripps Institution of Oceanography, University of California San Diego. This is an existing computational facility that can establish a virtual web address for the site (<http://ccs.lternet.edu>) that presents the site as part of the LTER community (Baker and Brunt, 2001). The data repository will be organized to facilitate rapid information exchange and online data documentation while supporting platform independence and low maintenance costs. As a site seeking to join LTER in its third decade as a network, CCE benefits from the collective experience of established LTER sites (Bowser, 1986; Michener and Brunt, 2000; Hobbie, 2003).

Information Management:

The mission of information management (IM) is to preserve data and support science over the long-term with the most appropriate and current technology (Figure 1; Karasti and Baker, 2004). This broader concept of data management includes responsibilities that support communications, plan toward interoperability, and facilitate documentation. For instance, communications involves mail lists, event information capture, field document preservation, and a publication list of pertinent site digital artifacts from articles to abstracts, from photographs to meeting notes.

Information Manager: From the beginning of proposal discussions, data management has been an integral part of the planning for the CCE LTER. The CCE information manager, K. Baker is a co-PI on the project, overseeing data management, information flow, and system design with a delineated budget for a component recognized as critical to the success of long-term science. As a bio-optical researcher for two decades and the Palmer LTER Information Manager (IM) since 1991 (Baker, 1996; 1998), she draws upon a unique experience base in scientific research, data management, LTER community, and information studies and is working with the IOD team and the larger SIO community to create infrastructure and processes that support collaborative work

through independent resources for information science and computer-supported cooperative research.

Information Environment: An information system ties together in concept and in design a multitude of elements critical to the success of a long-term research site. Figure 2 is a conceptual schematic of the CCE information system: administrative modules include a data dictionary and bibliographic citations, data and metadata elements, and web delivery. The data input from diverse sources is indicated here by the sampling groups/studies of measurements: time-series, process, and model results.

The concept of infrastructure with sociotechnical elements is the subject of ongoing research (Star and Ruhdler, 1996; Karasti and Baker, 2004). The computational infrastructure for the CCE LTER will be provided by the IOD computational center. As a member of IOD, Baker has been working closely with the IOD computational systems manager over the last year to design a broadened information environment including contemporary tools and techniques that enable collaborative science. The IOD center emphasizes open source software and takes into account technological change through focus on system evolution and data convertibility. The central data archive will be a backup of each individual investigator's datasets and, in addition, will itself be backed up on a regular schedule. In coordination with the IOD systems team in year 1, a web and file server will be purchased, installed, and maintained for CCE. Design and development of a web site is planned in coordination with existing SIO and IOD web development teams. Continuing support for the education and outreach website will be an integral part of this effort.

Information System: An information system contains multiple layers for storage, access, discovery, and for interface to users, systems, and analysis packages. CCE will design to converge with the oceanographic system evolution of DODS (distributed ocean data system) to NVOODS (National Virtual Data System) & OPeNDAP (Accessing Data in a Distributed, Heterogeneous Environment) that brings interoperability to the core of oceanographic systems. CCE will build from both the CalCOFI system and the USJGOFS data system recently installed at IOD. The USJGOFS database is object oriented, queriable, and provides immediate web data display for data exploration and brings a community of partners working to take advantage of middleware interfaces such as the NVOODS Oceanographic system that handles a range of data formats and provides an interface to an array of applications packages ranging from MatLab Toolkits to Ocean Data Viewer (ODV). An ongoing effort to combine CalCOFI zooplankton and hydrographic data includes the CalCOFI relational database (in Microsoft Access) being implemented through Live Access Server (LAS) to the National Virtual Ocean Data System (NVOODS; <http://ferret.pmel.noaa.gov/NVOODS/servlets/dataset>), an approach that designs for independence from platform and database environment. Thus there are utilities in place and under development to permit a variety of oceanographic data formats to work with LAS, a system being implemented by the National Marine Fisheries Service, an active CCE partner.

Data Management:

Metadata: Data documentation takes the form of developing study and dataset metadata as well as capturing standard practices and procedures. Although quality control for both field data and metadata is the responsibility of the individual investigators, metadata forms will be developed and readily available through file transfer and/or through web access. As shown in Fig. 3,

appropriate metadata can be used both to create a local dynamic data catalog as well as to serve data in an EML format to the LTER Network data catalog.

The CCE information systems will build from existing data methods, expanding where necessary to ensure interoperability with current systems of partners and with future systems of interest. The CalCOFI metadata will be augmented as needed during the mapping process to the LTER metadata standard, Ecological Metadata Language (EML; Michener et al, 1997). A data translation of the Palmer LTER metadata to both the Ecological Metadata Language and to incorporation in US Joint Global Ocean Flux System (USJGOFS) system recently installed at IOD adds to community focus on metadata and data transportability.

Data Design: We will develop a common vocabulary in the form of term lists and data dictionaries. For example, a 'study' consists of either a field cruise or other self-contained oceanographic interval representing a suite of related measurements. Within each study are a suite of pre-defined data sets. Event documents will include a study overview, a participant list describing who was on site for the study, and an event log listing chronologically the type and location of measurements, and relevant field notes. Work will focus on developing metadata forms in collaboration with participants in order to ensure there is an understanding of the need to devote time to data description in addition to the traditional data use.

Data Availability and Data Policy: Long-term datasets will be posted online as rapidly as possible so that investigators can have other component data available while evaluating and quality assuring their own contributions. CCE participants will have accounts on the IOD server so they can be networked directly to the CCE central archive or alternatively will have web access. The majority of project documents will be available to the public immediately. The group will develop a data policy in line with LTER standards and will define the rules of data sharing consistent with the NSF policy that datasets be accessible online within 2 years of collection.

Broader Participation:

Recognizing the value of multi-site coordination among LTER information managers, the CCE information manager will participate in the LTER network data management community through attendance at annual IM meetings as well as other LTER meetings such as the upcoming portal training workshop at the San Diego Supercomputer Center (SDSC) and the next LTER All-Scientists Meeting. Discussions are underway to establish new research links with the SDSC for data-intensive research programs such as our new CCE site.

As Palmer LTER information manager, K.Baker has contributed to the LTER community in a variety of roles: leading a multi-site team to describe the LTER Network Information System (Baker et al, 2000), establishing the LTER Newsletter Databits with a rotating editorship (Baker and Brunt, 1999), and participating as a six year member of the LTER IM Executive Committee. Her recent work includes leading a grant focusing on digital library information flow with SDSC and the University Library (Baker et al, 2002) as well as ongoing work with the Communication Department Chair (G.Bowker) and a researcher at the Department of Information Process at Oulu University (H.Karasti) contributes to new perspectives on information system design and collaborative science (Bowker, 2000; Karasti, 2001; Baker et al, 2002; Karasti et al, 2003).

(See separate References section for cited references.)

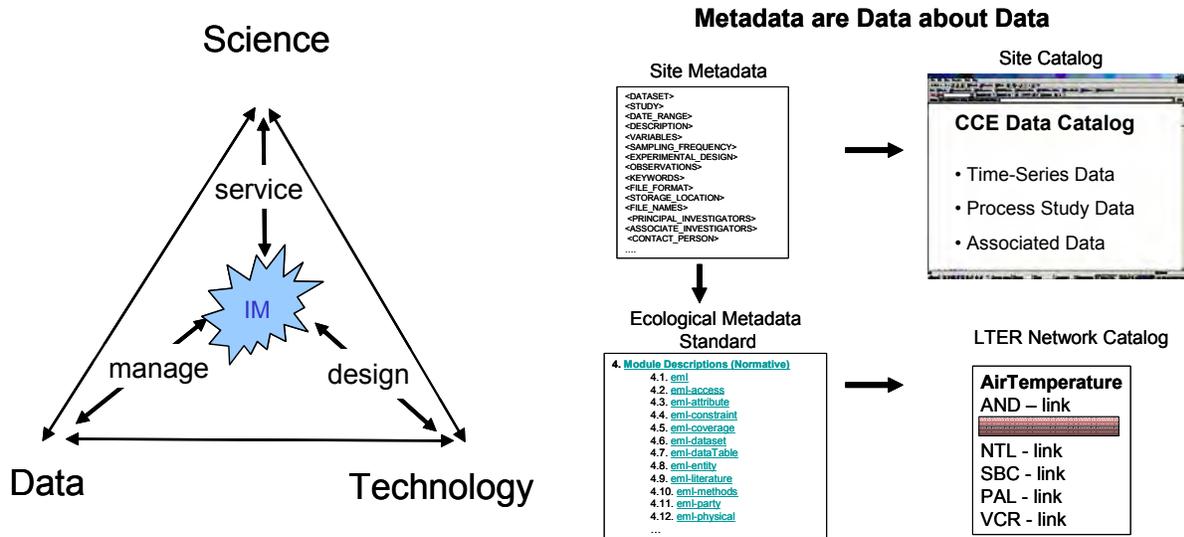


Figure 1. Elements of Information Management Work: managing data, supporting science, and designing technology.

Figure 3. Elements of data access using metadata to create dynamic data catalogs.

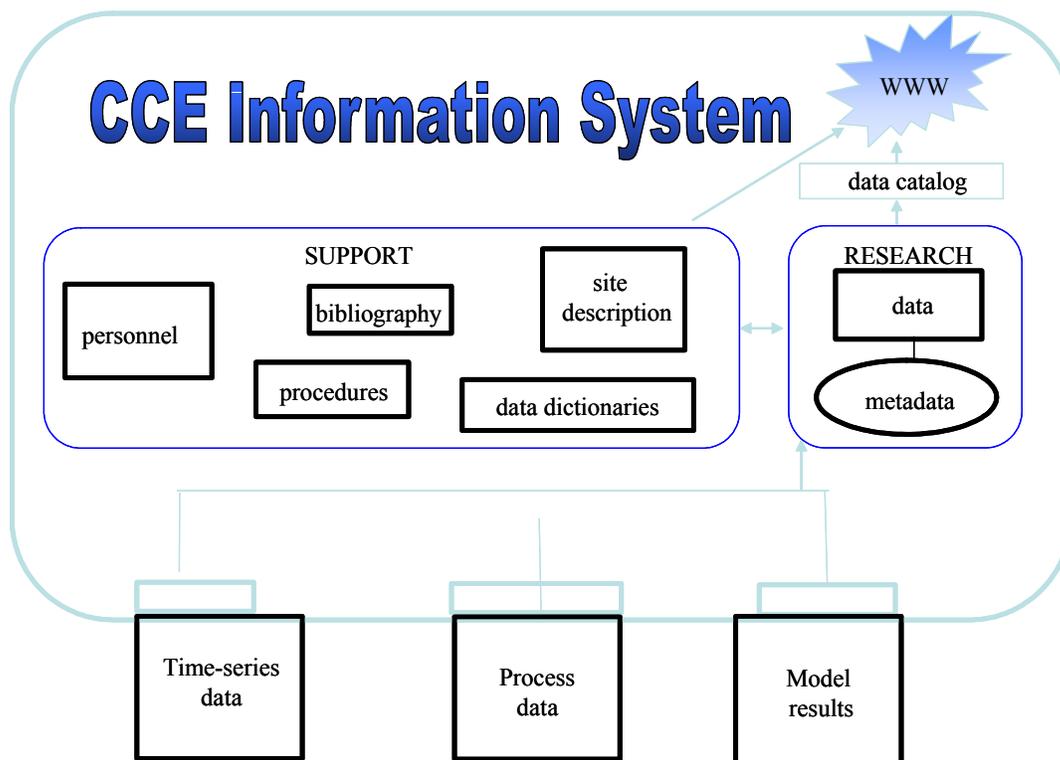


Figure 2. Elements of an LTER Information System including support modules and data-metadata research modules visible on the web; data input is represented as a diverse set of data group inputs.

Education and Outreach

The LTER Education Strategic Plan asserts that “*LTER education addresses some of the most important but vexing objectives for ecological and environmental education; that is, it uses outdoor, inquiry-based teaching and learning to build science literacy; it creates effective strategies for interdisciplinary and collaborative learning about ecology; and it teaches about local ecosystems while fostering an understanding of distant ones as well.*”

Addressing the goals articulated in this plan, the PIs have, with the guidance of the *California Center for Ocean Sciences Education Excellence* (CA COSEE), crafted a plan to extend the benefits of the proposed research well beyond the scientific community. In addition to supporting post-doctoral researchers and training graduate students, the CCE LTER PIs will partner with a trio of Informal Science Education (ISE) organizations poised to efficiently and effectively convey the scientific goals, methodology and results of this major research undertaking to students, teachers, and the public.

K-12 Education and Outreach

The CCE LTER will hire an Education and Outreach Coordinator to manage the site’s E&O activities, as well as to participate in ongoing E&O development with colleagues across the LTER Network. Among the E&O Coordinator’s primary responsibilities will be orchestration of mutually beneficial partnerships between CCE LTER scientists at all levels (PIs, post-docs, grad students, technicians) and key staff members at the Birch Aquarium at Scripps (BAS), the Ocean Institute (OI) and Aquatic Adventures (AA). In addition, the Coordinator will focus on fiscal development, both public and private, to strengthen and support specific LTER E&O programs that may include: teacher professional development workshops; development of curricular materials; creation of educational videos; design and construction of science center exhibits/learning stations; participation in NSF’s Research Experiences for Teachers (RET) and Undergraduates (REU) programs; and application for NSF’s Communicating Research to Public Audiences grant(s), as well as annual \$15K LTER E&O supplements. The Coordinator will also contribute to the CCE LTER web site, coach teachers who participate in at-sea operations, and, as appropriate, represent researchers and their outreach efforts at national meetings of scientists and educators.

Birch Aquarium at Scripps (BAS): The E&O Coordinator will work in association with the Birch Aquarium, the interpretive center for Scripps. BAS has more than 350,000 visitors per year including more than 75,000 school children. A central component of the BAS mission is the interpretation of Scripps research for the public. In support of the BAS mission, a talented team of professional science educators has created a range of Earth and ocean science programs that include hands-on K-12 classes, teacher professional development workshops, and public programs. BAS facilities include aquarium displays featuring the variety of ecosystems encountered along the California coast, a 70,000-gallon kelp tank, and a new *Ocean Exploration Center* that will be a venue for exhibits on current Scripps research. BAS will work closely with the E&O activities of the CCE LTER and will spearhead the creation, implementation and dissemination of new E&O programs and exhibits born out of this research.

Ocean Institute (OI): The Ocean Institute at Dana Point, CA serves more than 100,000

students each year through its in-depth, inquiry-based, standards-aligned programs. OI's focus on providing research experiences for students makes it an ideal partner in the CCE LTER efforts to integrate research and education. Daily student cruises on the OI's 70-foot *R/V Sea Explorer* to an oceanographic station in close proximity to CalCOFI station 90.28 offer an excellent opportunity for sampling and data collection that will fulfill two major objectives: 1) generating a coastal, high-frequency time series of hydrographic and phytoplankton pigment data that will provide an improved view of how coastally trapped waves from the south propagate along the coast and 2) giving students an opportunity to become involved in an ongoing scientific research project. The PIs will provide OI staff with a fluorometer, training in analytical procedures and data collection protocols, and support for calibration of analytical equipment. The PIs will also explore the possibility of training OI staff to screen plankton tows and trawls for the presence of indicator species. Working with the CCE LTER E&O coordinator, the OI team will develop student programs and teacher workshops built around LTER research. These programs may serve as a springboard for a "student experiments at sea" program in which students design experiments to be conducted during LTER cruises. OI's educators will ensure the alignment of programs with education standards and conduct program evaluation.

Aquatic Adventures (AA): Aquatic Adventures is a 6-year-old, private, non-profit organization with funding from government, foundation, corporate, and individual contributions. Aquatic Adventures' mission is to connect underserved youth to science through a variety of intensive hands-on learning in classroom outreach and summer camps, after school mentoring programs that bring together high-achieving high school students and at-risk youth and study abroad experiences. Through Aquatic Adventures' tuition free programs, over 3500 elementary, middle and high school students in 25 schools were reached last year. In support of AA's programs CCE LTER scientists will host laboratory visits at SIO to give students insight into the process of ocean science. Each PI is expected to host 1-2 of these visits per year. These visits will provide unique opportunities for students with little or no experience in the sciences to gain first hand knowledge and interact directly with scientists. AA's staff will provide preparation and follow-up to maximize the scientific benefits of each visit.

Graduate Education

In addition to K-12, public outreach, and research opportunities for graduate students and postdoctoral investigators, the CCE LTER site will interface with a new graduate education pathway at SIO. The *Center for Marine Biodiversity and Conservation* (CMBC) at SIO recently received an *Integrative Graduate Education and Research Traineeship* (IGERT) award entitled "*Marine biodiversity: Understanding threats and providing solutions.*" The centerpiece of CMBC's new program is training in interdisciplinary, team-based, problem-solving methods to address topical problems in marine biodiversity. Environmental problems will be examined from a socioeconomic, legal, and policy perspective as well as scientific view. The scientists participating in this LTER site, many of whom are also faculty associated with the CMBC, will offer the IGERT Interdisciplinary Problem Solving graduate seminar with a focus on the challenges of making management decisions for marine resources in the face of environmental uncertainty. The seminar will draw on the ecosystem shifts being studied

at the CCE site, and is expected to be taught in collaboration with our colleagues at the Southwest Fisheries Science Center, the UCSD Department of Economics, and the Graduate School of International Relations and Pacific Studies.

Additional components of the CCE E&O plan

<p>Scientists' direct contributions to BAS, OI, and AA activities that integrate research and education</p>	<ul style="list-style-type: none"> • Providing teachers with opportunities to participate in research cruises; • Giving on-site (or teleconference) presentations during student and teacher programs; • Offering input on the design and scientific focus of public exhibits • Contributing research equipment and real time data/imagery that students can analyze and interpret. • Participating in a recently launched CA COSEE teacher professional development program focused on marine ecosystems • Contributing to an innovative CA COSEE undergraduate/graduate course, <i>Communicating Ocean Science</i>, to be taught at SIO/UCSD beginning in 2005
<p>Media relations</p>	<p>SIO has an excellent communications office that will actively publicize CCE LTER research accomplishments through local and national media.</p>
<p>Educational Web Site</p>	<p>The CCE LTER web site will function, in part, as a mechanism for communicating and disseminating E&O products via the web.</p>
<p>Pt. Reyes Bird Observatory (PRBO)</p>	<p>PRBO Outreach and Education Department will collaborate with the CCE LTER E&O Coordinator to create 10-15 minute educational videos detailing studies of climate variability and responses of pelagic ecosystems.</p>

RESULTS FROM PRIOR NSF SUPPORT

M.D. Ohman: OCE-0110300, GLOBEC 2000: Long-term changes in California Current Zooplankton Assemblages and Euphausiid Population Dynamic Parameters \$760K, 3/01-2/06.

We have resolved 'regime shift' dynamics in certain representatives of the zooplankton, especially salps, euphausiids, doliolids, and selected species of calanoid copepods. Such shifts are clearly discernable at the species level but weakly so if the data are aggregated. Ocean-atmosphere changes in the North Pacific in 1976-77 and more recently in 1998-99 were accompanied by a strong rearrangement of the zooplankton assemblage, of opposite sign at the two transitions. Zooplankton faunistic studies, stable isotope analyses, and analyses of hydrographic data suggest that some changes first observed in 1999 have largely persisted since that time. Some taxa of zooplankton, particularly those with more subtropical biogeographic affinities, show a clear association with the PDO. Our results suggest that the mechanisms *initiating* such changes are alterations in north-south transports, but they're *sustained* by changes in situ. Analysis of the stable N isotopes of 4 species of zooplankton over 51-years revealed no linear trend, but we discovered a strong, but reversible, El Nino-related enrichment in ^{15}N in 3 out of the 4 species. We concluded a comprehensive analysis of the effects of changes in sampling gear on potential collection bias for 17 major taxa of zooplankton, and the effects of sample pooling on bias in diversity indices. Working with a climate scientist we have identified characteristics of atmospheric circulation and sea surface temperature that define the primary modes of ocean variation associated with dominance of different zooplankton taxa, which suggest a ~3 month forecast interval for predicting some zooplankton responses to changes in climate forcing. To date this grant has supported the research of 8 graduate students, 1 summer intern, 1 postdoctoral investigator, numerous undergraduates, and 4 technical staff. Among the people supported are 2 African American women and 2 Latino participants.

Ohman publications resulting from this NSF support

- Abraham, C.L. & W.J. Sydeman. 2004. Ocean climate, euphausiids, and Auklet nesting: Inter-annual trends and variation in phenology, diet and growth in a planktivorous seabird. *Mar Ecol Prog Ser* (in press)
- Eiane, K. & M.D. Ohman. 2004. Stage specific mortality of *Calanus finmarchicus*, *Pseudocalanus elongatus* and *Oithona similis* on Fladen Ground, North Sea, during a spring bloom. *Mar Ecol Prog Ser* (in press)
- Lavaniegos, B.E. & M.D. Ohman. 2003. Long term changes in pelagic tunicates of the California Current. *Deep-Sea Res II* **50**: 2493-2518.
- Brinton, E. & A. Townsend. 2003. Decadal variability in abundances of the dominant euphausiid species in southern sectors of the California Current. *Deep-Sea Res II* **50**: 2469-2492.
- Goetze, E. 2003. Cryptic speciation on the high seas; global phylogenetics of the copepod family Eucalanidae. *Proc Roy Soc Lond B* **270**:2321-2331.
- Ohman, M.D., K. Eiane, E.G. Durbin, J.A. Runge & H.-J. Hirche. 2003. A comparative study of *Calanus finmarchicus* mortality patterns in five localities in the North Atlantic. *ICES J Mar Sci*
- Ohman, M.D. & E.L. Venrick. 2003. CalCOFI in a changing ocean. *Oceanography* **16**: 76-85.
- Rau, G.H., M.D. Ohman & A.C. Pierrot-Bults. 2003. Linking nitrogen dynamics to climate variability off Central California: A 51 year record based on $^{15}\text{N}/^{14}\text{N}$ in CalCOFI zooplankton. *Deep-Sea Res II* **50**: 2451-2467.
- Batchelder, H.P., 14 others. 2002. The GLOBEC Northeast Pacific California Current System program. *Oceanogr* **15**:36-47.

- Eiane, K., D.L. Aksnes, M.D. Ohman, S. Wood & M.B. Martinussen. 2002. Stage-specific mortality of *Calanus* spp. under different predation regimes. *Limnol Oceanogr* **47**: 636-645.
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- Ohman, M.D. H.-J. Hirche. 2001. Density-dependent mortality in an oceanic copepod population. *Nature* **412**: 638-641.

Ph.D. theses

- Curtis, A. 2003. Pattern in Space and Time of Clupeoid Fish Eggs in the California Current Region. Ph.D. thesis, U.C. San Diego.
- DeRobertis, A. 2001. Small-scale spatial distribution and swimming behavior of euphausiids in relation to visual predation risk. p. 1-242. Ph.D. thesis, U.C. San Diego.
- Rebstock, G.A. 2001. Long-term changes in the species composition of calanoid copepods off Southern California. p. 1-240. Ph.D. thesis, U.C. San Diego

K. Barbeau, OCE-20950, *Iron speciation and cycling in the Eastern Tropical North Pacific*, \$125,000, 9/1/02–8/31/05.

We are in year two of this project, and have recently completed the second of two planned cruises to the Eastern Tropical North Pacific over the oxygen minimum zone area. Data from these cruises indicates that this area exhibits a unique layered structure in terms of the biological community and degree of Fe limitation experienced in the euphotic zone, with a nitrate-limited community in the mixed layer overlying an Fe-limited population at the chlorophyll maximum near the top of the oxycline. On the most recent cruise, we also obtained the first direct evidence for the presence of reduced iron species in suboxic zone water, using a chemiluminescent flow injection analysis technique. We expect to present data from this cruise at the 2004 Environmental Bioinorganic Chemistry Gordon Conference. This project has supported one postdoc, Julian Herszage, in the development of electrochemical analysis methods, an important goal in his postdoctoral training. One graduate student, Brian Hopkinson, has participated in both cruises and is learning valuable techniques for sampling and analysis of trace metals at sea. This project also supported an REU student from Long Island University, Joshawna Nunnery, who worked in our lab from June - Dec 2003 and participated in the November 2003 cruise to the Eastern Tropical North Pacific.

Barbeau publications from this NSF support: None to date

Ralf Goericke: OCE93-11244 (JGOFS), *Response of Arabian Sea phytoplankton biomass, pigmentation, growth rates, and community structure to seasonally varying physical forcing*, \$360,000, 6/94 – 5/97.

This project characterized phytoplankton community structure in the monsoonal Arabian Sea, primarily using pigment-based methods. During TN43 and 49, we observed a secondary fluorescence maximum at the top of the oxygen minimum zone. 99% of the pigment-biomass in

this layer was *Prochlorococcus sp.*, which was confirmed using flow-cytometry during TN49 by R. Olson. Both simulated *in situ* and *in situ* pigment labeling experiments showed extremely high rates of primary production; off the coast of Oman it exceeded $200 \text{ mg-C m}^3 \text{ d}^{-1}$; values typical of oligotrophic central gyres were only measured at the southern-most station; rates in the mixed layer were $10 \text{ mg-C m}^{-3} \text{ d}^{-1}$. We observed high growth rates (0.9 to 1.2 d^{-1}) close to the coast, matched by high specific rates of biomass change, (0.3 to 0.6 d^{-1}), consistent with results from dilution experiments. Further offshore, rates were variable, ranging from 0.25 d^{-1} in the oligotrophic area to 1.2 d^{-1} in an offshore filament with high nutrient concentrations. Growth rates for dinoflagellates and pelagophytes were consistently lower than growth rates of diatoms or cyanobacteria. When plotted against nitrate - a proxy for the availability of nitrogen - growth rates varied according to Monod-kinetics; evidence that phytoplankton growth rates in the Arabian Sea during the NE and SW monsoon was limited by nitrogen or by a covarying nutrient or growing at physiologically constrained maximum rates. Grow-out experiments with high-nutrient water collected from the surface suggested that phytoplankton was not nutrient limited since biomass more than tripled over the 3-d incubation time. Diatoms dominated phytoplankton biomass at the end of the incubation period even though they were almost absent in the offshore waters. It is hypothesized that diatom abundance in the water is controlled by grazers, which were absent from the incubation bottles.

Goericke publications from this NSF support:

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This project was a component of the U.S. JGOFS Study (AESOPS) of primary productivity, food-web dynamics, and biogeochemical cycling in the Antarctic Polar Front Zone (APFZ) of the Southern Ocean. On 4 cruises spanning the production season (Oct-Mar), we determine the temporal and spatial patterns in the abundance and biomass of microplankton communities, estimated taxon-specific rates of phytoplankton growth and microzooplankton grazing, and

evaluated the relative influences of iron, light and microzooplankton grazing in controlling phytoplankton standing stock and growth rate. Funding from this and other NSF-JGOFS projects (1992-present), has been acknowledged in >60 papers to date and has provided salary support and/or research opportunities for 15 graduate students, 4 post-docs and several undergraduates. Various aspects of these project were included in 6 M.S. Theses and 5 Ph.D. Dissertations.

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A. Miller: OCE-9711265, *Analysis of Decadal Variability in the North Pacific*, N. Schneider (co-PI) \$335,000, 10/97-9/00; **OCE-0082543** (renewal), N. Schneider (co-PI) \$497,813, 11/00-10/05.

This work emphasized the use of models as a tool for the analysis of low-frequency variability in the North Pacific. Decadal signals were found that move in the thermocline along lines of constant potential vorticity from the subduction region in the central North Pacific to the western Pacific with a transit time of eight years (Schneider et al. 1999a); south of 18°N, tropical Ekman pumping was found to drive thermocline variability (Schneider et al. 1999b). The main thermocline of the North Pacific subpolar gyre shoaled from the 1970's to the 1980's as a response to decadal-scale changes in basin-scale wind stress curl (Miller et al. 1998). Our post doc (Aud et al. 1998, 2001) analyzed the upper ocean heat balance in terms of the diabatic and the adiabatic parts of the heat content for several regions in the North Pacific; he then evaluated

COADS and NCEP surface fluxes in the context of forcing 50-year simulations of the Pacific. Oceanic decadal variability was described in the context of possible effects on ecosystems (Miller and Schneider 2000), and changes in ocean stratification were related to nutrient fluxes to the photic zone and consequent biological changes (McGowan et al. 2003). A regional eddy-resolving ocean model showed that heat flux warming increased the stability of the water column and reduced the strength of upwelling in spite of increased upwelling-favorable winds (Di Lorenzo et al. 2003). A 130-year coupled-model showed that the enhanced variance in the oceanic streamfunction and SST that is centered on the Kuroshio-Oyashio Extension (KOE) is likely due to the short record length of the simulation or to remote forcing (Schneider et al. 2002); 10-25% of the variance of observed wintertime KOE SST was predicted up to 3 years in advance by Rossby wave dynamics (Schneider and Miller 2001). There have been fourteen publications on which Miller is a co-author; support was provided for one graduate student (Di Lorenzo) and one post-doc (Auad). This grant also supported a workshop on climate forcing and biological feedback (Miller et al. 2003).

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