Ocean observing in the Monterey Bay National Marine Sanctuary: CalCOFI and the MBARI time series

A Report to the Sanctuary Integrated Monitoring Network (SIMoN)
Monterey Bay Sanctuary Foundation
Monterey Bay National Marine Sanctuary
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1. Introduction

The Monterey Bay National Marine Sanctuary (MBNMS) encompasses much of the central California coast between San Francisco Bay and Point Conception. The oceanography of the MBNMS has received considerable study. Much of this work was begun under the auspices of the California Cooperative Oceanic Fisheries Investigations (CalCOFI), originally established in 1949 to study the declining sardine fisheries off the North American west coast. Over the decades CalCOFI has evolved in size, focus and sponsorship. For the past two decades the Biological Oceanography Group at MBARI has conducted a focussed program of observation on CalCOFI Line 67, within and offshore of Monterey Bay in the MBNMS (Figure 1).

This report introduces the CalCOFI and the MBARI programs as they relate to each other and oceanography within the MBNMS. Below we provide a brief review of MBNMS oceanography with summary graphs, and also provide introductory links to the extensive websites and detailed research papers of both programs. The document is intended to provide an entrance point for people interested in oceanography within the MBNMS, and may be expanded in future years as CalCOFI and MBARI's 'evolution' continue.

2. CalCOFI history --- A national treasure

In the late 1940s following heavy fishing during World War II, sardine landings in California were declining and the California Division of Fish and Game, the California Academy of the Sciences, Scripps Institute of Oceanography and the U.S. Fish and Wildlife Service joined forces to develop the California Cooperative Sardine Research Program. The goal was to understand the physical and biological components of the marine ecosystem as they affected sardine stocks.

Before this goal was achieved, however, the sardines vanished. In the early 1950s the entire fishery collapsed, with fishermen burning their boats for insurance and canneries left standing empty. In 1953 the California Cooperative Sardine Research Program was scaled-back and renamed the California Cooperative Fisheries Investigations (CalCOFI). Oceanographic cruises and data collections were largely restricted to the southern California bight, where remnant sardine stocks persisted.

Funding became uneven and difficult, but with great credit to the personnel who devoted their careers to it, the program survived and some cruises continued to venture north of Point Conception and south of San Diego. Over the years data accumulated, and with the advent of computers the records were assembled into a database which includes hydrographic and chemical measurements (temperature, salinity, oxygen, nutrients such as nitrate), plankton data (both plant and animal) and more recently, the distribution and numbers of apex predators (birds, large fish, and mammals). In spite of its ups and downs, the CalCOFI time series of data collections is now recognized as the longest and most complete oceanographic record in the world, and in 1997 was identified as a national science treasure (http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=1112&ParentMenuId=218).

3. Global climate change and ocean observing

The 1982-83 El Niño changed the way oceanographers view the world. Over an 18-month period the idea of global climate change suddenly became real, as strong climate fluctuations occurred globally and over short, not-geological time scales. This lesson has been repeated every 3-7 years by subsequent El Niño's. Because physics of the atmosphere and oceans are tightly coupled, climate change is observable in both media. With the unchecked rise of atmospheric CO_2 levels, concern over long-term climate warming and its effects on man's activities has steadily increased, and has now taken center-stage in climate change discussions.

If data records span the time scale of interest, climate change is observable and can be studied and at least partly understood. Thus long-running programs such as CalCOFI, which in the 1960s and 70s had often been regarded as unexciting monitoring efforts, were recognized instead to be priceless records of climate and ocean variability. With this realization, new 'ocean observing' programs have also sprung up, and off the west coast of North America many of these, including parts of CalCOFI, have been assembled under the umbrella organizations PaCOOS (http://www.pacoos.org), CeNCOOS (http://www.cencoos.org/index.html), and IOOS (http://ocean.us). Thus CalCOFI's original emphasis on sardines has broadened into a present emphasis on climate change. And, finally closing the circle, it appears that the 1950s crash of the sardines has now been explained --- over 50 years later --- by global climate fluctuations (http://www.sciencemag.org/cgi/content/full/299/5604/217).

4. Ocean observing in the MBNMS --- the MBARI time series

One of CalCOFI's 'descendant' programs is the Monterey Bay Aquarium Research Institute (MBARI) time series program along CalCOFI Line 67 off central California (Figure 1). Even though 'L67' originates in Monterey Bay, at what was the center of California's sardine fishery, it has been occupied only irregularly by CalCOFI ships, particularly since the 1970s (see Appendix 1). In 1988 MBARI researchers reactivated L67 with regular oceanographic cruises to measure basic physical, chemical and biological variables. For 18 years now the nearshore portion of L67 in Monterey Bay has been occupied by ship every 2-3 weeks (1988-2006; Monterey Bay cruises not listed in Appendix 1), and the California Current portion has been occupied quarterly to 300 km

offshore (1988-91, interrupted until 1997-2006, see Appendix 1). These cruise data have been augmented by high-frequency time series data from moorings both within and offshore of Monterey Bay (since 1992). The program has documented spatial dynamics both within and offshore of Monterey Bay, seasonal cycles, El Niños and La Niñas, decade-scale cycles (*e.g*., Pacific Decadal Oscillation), and is now working to separate all these forms of variability from the global warming signal.
Below we describe the MBARI time series' basic findings and provide summary graphs. Many more detailed graphics of the MBARI results are located at http://www.mbari.org/bog/Projects/CentralCal/summary/ts_summary.htm and http://www.mbari.org/bog/Projects/secret/default.htm. Although this document focuses on the MBARI time series, it is only one of several CalCOFI offspring within the MBNMS; many of these are summarized at the SIMoN website, at http://www.mbnms-simon.org/. CalCOFI has remained active far longer and over a far greater geographic area than the MBARI 'descendant' describe here; CalCOFI as it now exists is described at http://calcofi.org/.

5. North Pacific Subtropical Gyre and the California Current System

The Pacific Ocean off western North America is a classic eastern boundary current region (reviewed by Pennington *et al.*, in press, at http://mbari.org/staff/peti/Pubs/CMTT.Carbon%20Cycling.7Jun05.pdf%20). In this system near surface flow of the North Pacific Subtropical Gyre can be divided into three regions (Figure 2). Offshore, in the central Pacific beyond about 1300 km from North America, warm and salty North Pacific Central Gyre waters form a southward-flowing layer about 250 m deep. Second, between the Central waters and 150-200 km west of North America, the California Current (CC) also flows southward at 15-30 cm/s (0.6-1.2 km/hr) as a 1200 km broad and 250 m deep surface current. CC isolines (thermocline, halocline, nutricline; Figure 3) shoal towards the east due to a basin-scale geostrophic adjustment termed 'pycnocline tilting', caused by interaction of the flow with the earth's rotation (Coriolis). Maximum velocity occurs near the CC's eastern margin, on average only 150-200 km offshore, and this 'CC jet' or core transports the CC's lowest salinity water (see Figures 2, 3; and Collins *et al.*, 2003, at http://www.mbari.org/staff/peti/Pubs/Collins%20et%20al.L67.2003.pdf). Spring and summer maxima in CC jet velocity are associated with seasonal maxima in CC pycnocline tilting. Thirdly, inshore of the CC jet, the CC interacts with the North American continent in a region we call the Coastal Upwelling System (CUS), where coastal currents and mesoscale phenomena dominate. In spring and summer, seasonal northwesterly winds drive a coastal upwelling circulation in the CUS characterized by equatorward flow of near-surface coastal upwelling jets with associated eddies and fronts that extend offshore to the CC (see Section 6, below). This wind-driven equatorward circulation overlies the poleward-flowing California Undercurrent, which has maximum velocity near 10 cm/s at 100 but reaches to at least 1000 m (m (mean core velocity, 4.2 cm/s). In winter, northwesterly winds weaken or are replaced by southerly storm winds. Under these conditions the California Undercurrent surfaces where it is called the Inshore Countercurrent or Davidson Current which flows northwards 0-100 km offshore, also at 5-10 cm/s. The CC and CUS with its California Undercurrent, Inshore Countercurrent and coastal upwelling circulation are together termed the California Current System, and the MBNMS lies wholly within this system.

6. Coastal upwelling

The oceanography of the MBNMS is strongly influenced by the process of coastal upwelling (reviewed by Pennington and Chavez, 2000, at http://www.mbari.org/staff/peti/Pubs/Seasonal_fluctuations.H3-M1.pdf). In general, coastal upwelling occurs along eastern ocean margins when equatorward winds act in combination with the earth's rotation (Coriolis) to move surface waters offshore, drawing colder and saltier (and thus denser) water to the surface nearshore (see Figures 3, 4). This 'upwelled' water occurs as a cool band along the coast, typically several 10's of km broad, separated from warmer offshore waters by a variable series of fronts, plumes and eddies which can extend >100 km offshore. Upwelled water is nutrient-rich, and supports high levels of phytoplankton and higher trophic level production. Off the western United States and Baja California, coastal upwelling occurs seasonally as described below.

7. Seasonal cycles

The seasonal cycles of Monterey Bay were originally described by Skogsberg (1946), who divided the year into three 'oceanographic seasons' which are still in wide use today. These are introduced below with review text and graphs from Pennington and Chavez (2000, at http://www.mbari.org/staff/peti/Pubs/Seasonal_fluctuations.H3-M1.pdf).

7.1 Spring/summer upwelling season (Feb-Aug). Spring and summer is associated with increased equatorward wind, southward transport of surface water, lowered sea level (centimeters), low surface temperatures and high salinities. For the MBNMS region, mean monthly winds are southward year round, but southward velocities and stresses increase seasonally in March-April (Figure 5), resulting in the 'spring transition' to upwelling conditions during these months. In a calculated average year in central Monterey Bay (Figure 6, stations M1 and H3), isolines begin to shoal in February, but minimum surface temperatures occur intermittently March-June (11.5-12 ^{o}C; Figure 6A), and deeper isotherms, salinity and nitrate data all indicate the upwelling period 'climaxes' in June (minimum isoline depths; Figure 6A-C) even though upwelling begins several months earlier. The annual cycle of nitrate is similar to that of salinity (Figure 6B-C). Nutrients, sunlight, and some degree of water column stratification lead to high primary production and chlorophyll values during the upwelling period (Figure 7A-B). The upwelling period flora is dominated by diatoms, especially *Chaetoceros spp.* A decay phase (July-August) of the upwelling period can also be differentiated from an active phase (February-June). During July-August surface salinities remain high but temperatures rise; subsurface isotherms and isohalines deepen (Figure 6B; 50-200 m). This latter period represents a seasonal decline of the upwelling period, probably due to surface warming by sunlight and weakening NW winds (Figure 5B-C).

7.2 Fall oceanic or California Current season (Aug-Oct). As equatorward winds weaken in late summer (Figure 5B-C), periods of 'relaxation' from upwelling become more common and warm, fresh California Current water ultimately moves onshore at the surface to mix with and replace upwelled water. In the graph below there is little temperature transition in late-August (Figure 6A). Instead, surface warming begins in late-June and July and surface waters remain warm (13.5-15 ^{o}C) through most of November. However, the salinity data show a striking reduction in salinity to almost 50 m beginning in late-August (to 33.5-33.6 pss), and this freshening almost certainly represents an influx of California Current water (the core of the CC is relatively fresh, typically 32-33 pss at 36^{o} N). Phytoplankton blooms continue to develop intermittently during the oceanic period (Figure 7A-B), when they are composed primarily of oceanic picoplankton. Apparently enough nutrients are injected into the euphotic zone via occasional fall upwelling to support these blooms.

7.3 Winter Davidson or Inshore Countercurrent season (Nov-Jan). Associated with a weakening of equatorward winds (Figure 5B-C), northward surface flow develops in winter as an inshore countercurrent in winter off of much of western North America; north of Point Conception the current is known as the Davidson Current or Inshore Countercurrent. From December through early-February, waters <100 m are warm relative to the upwelling period and characterized by a low thermal gradient (11-12 ^{o}C to ~100 m). This low thermal gradient is presumably caused by continued subsidence of deeper isotherms following the upwelling season (Figure 6A), and mixing by winter storms. Onset of the Davidson Current period is marked by little or no salinity increase relative to the oceanic period, apparently due to admixture with California Current water at this latitude and the presence of freshwater runoff in MB after November of some years. During the Davidson Current period, phytoplankton populations reach annual minima (Figure 7A-B).

8. Short-term variation – weather events

The highly-smoothed ‘average’ year contours presented above for Monterey Bay obscure the strongly episodic character of the system --- the raw time series (Figure 8) are far noisier than the smoothed contours presented so far, and this ‘noise’ is an important component of the data. As weather systems pass through, the wind fluctuates on a scale of days (Figure 5A-B), and the surface ocean responds with episodes of upwelling which are seen as short periods of cold, high salt and nitrate surface water (Figure 9). Phytoplankton, in particular, appear as strikingly pulsed blooms within the upwelling and oceanic periods (Figure 10A-B). Such phytoplankton blooms tend to occur during several days or weeks of moderately high nutrient availability (5-10 μM nitrate; Figure 9C), but not during the strongest upwelling episodes and represent both growth and advection. These weather-scale dynamics have been studied and modeled most recently during a Navy-funded experiment summarized at http://www.mbari.org/mb2006/default.htm. Still higher-resolution time series data from the moorings also show daily and hour-scale fluctuations not introduced here.

9. Interannual variation --- El Niño

The strong 1997-98 El Niño has been described for the MBNMS by Chavez *et al.*, 2002; http://www.mbari.org/staff/peti/Pubs/El_Nino.1997-1998.pdf, and the weaker 1992-93 El Niño is visible on Figures 9-10. El Niño's are observed off California as a reduction in equatorward winds, a 1-2 ^{o}C sea surface warming, an elevation of coastal sea level, unusually strong wintertime Davidson Current, a thickened mixed layer and deeper nutricline, and low chlorophyll concentrations and zooplankton abundances. Off California the events are primarily wintertime phenomena, but may also delay or weaken spring and summer upwelling seasons. In Monterey Bay the water column becomes warm and fresh relative to other years (Figure 9A-B) and the nutricline is depressed during the upwelling season (Fig. 9C). However during the weak 1992-93 El Niño, neither primary production nor chlorophyll values were strikingly reduced in Monterey Bay (Figure 10A-B). This was not the case during the strong 1997-98 event.

10. Decade-scale variation --- the Pacific Decadal Oscillation

In 1976-1977 a so-called 'regime shift' occurred which has been associated with decadal scale climate and ocean alterations in both hemispheres, and which persisted until 1998. This shift apparently marks a change in a 50-year cycle now known as the Pacific Decadal Oscillation (PDO). In the California Current the following changes were reported: (1) water to 300 m warmed and freshened and sea level has consequently increased; (2) near surface stratification increased, resulting in less upwelling of nutrients and reduced new production; and (3) zooplankton and salmon abundance declined. The PDO has also been implicated in Pacifc basin-scale fluctuations of sardine and anchovy stocks (http://www.sciencemag.org/cgi/content/full/299/5604/217). Following the 1997-98 El Niño, the northeast Pacific appears to have shifted back to cooler, higher nutrient and productivity conditions (Figure 11), and the PDO remains an active topic of study in our lab.

11. Decade to century scale variation --- global warming

In the face of all the above sources of variability, we have not, so far, detected the global warming signal in our Monterey Bay time series data. In fact, two opposing scenarios are predicted for global warming in the MBNMS. An older idea suggests that, because land warms more quickly than water, with global warming our NW sea breeze should *strengthen*, resulting in stronger upwelling, higher phytoplankton productivity, cooler surface ocean temperatures (and more fog too). In contrast, a newer idea suggests that, because the poles will warm more dramatically than the tropics, the trade wind system which also drives our NW sea breeze should *weaken*, thus resulting in weaker upwelling, less phytoplankton productivity, and warmer surface ocean temperatures (and less fog). Our state of ignorance is such that only time and continued observation will tell which, if either, scenario is correct.

12. Spatial variation --- CalCOFI Line 67

So far we have focussed on temporal variation within Monterey Bay. Equally strong changes occur, however, as one travels along L67 from the green-water Monterey

Bay offshore into the blue-water California Current (http://www.mbari.org/staff/peti/Pubs/Smoothed%20seasonal%20dynamics.2006.pdf). We have divided L67 into four fairly natural regions (Figure 12): (1) Monterey Bay (MB), 0-20 km from shore; (2) a Coastal Upwelling Zone (CUZ), 20-52 km from shore; (3) a Coastal Transition Zone (CTZ), 52-170 from shore where upwelling-derived eddies, jets and filaments mix with California Current water; and (4) the California Current (CC), 170-300 km from shore.

These zones are compared in Figures 13-14 with highly-smoothed seasonal curves. The main differences between zones are that (1) Seasonal cycles are strong nearshore (MB and CUZ) and consistent with coastal upwelling as the major driver, but much weaker offshore (CTZ and CC). The weak offshore cycles may represent damped and delayed propagation of the upwelling signal offshore via advection or thermocline perturbation; (2) Surface macronutrients peak nearshore during the upwelling period and are drawn down strongly during the oceanic period; (3) Biological production on and offshore is coupled to macronutrient levels. Diatoms dominate nearshore during the upwelling period and dinoflagellates dominate during the oceanic period. Among photosynthetic bacteria, *Synechococcus* is most abundant during the oceanic period but not offshore (CC) whereas *Prochlorococcus* is most abundant in winter and offshore (CC). Our lab does not collect zooplankton, fish or marine mammal data along L67, but some MBNMS zooplankton and marine mammal information can be obtained at http://swfsc.nmfs.noaa.gov/PRD/PROJECTS/CSCAPE/default.htm and http://www.mbnms.nos.noaa.gov/research/techreports/trbenson_3.html.

Our most recent occupation of L67 --- cruise 'S306' --- was during a MBNMS cruise aboard the NOAA ship MacArthur II (http://www.moc.noaa.gov/mt/index.html) during June and July of 2006. We had a very calm cruise reflecting the fact that upwelling along L67 has been weak this season. Detailed results for S306 are posted on the web along with those for almost 50 other L67 cruises conducted since 1997 (http://www.mbari.org/bog/Projects/secret/default.htm). Such cruise results are periodically synthesized and presented at scientific meetings or published in scholarly journals (see links above).

13. Conclusion

In the above we attempt to provide an introduction to the oceanography of the MBNMS, as revealed by the MBARI time series program. This program is a direct descendant of pioneering CalCOFI efforts --- efforts we also applaud as a national treasure. The results presented above are basic. To some degree this represents an effort to introduce and provide a readable entry point into MBNMS oceanography and the research programs within. But it equally represents our continuing ignorance about basic interactions within our neighboring ocean. As one example, we still have little idea what role heavy fishing during World War II played in the 1950s collapse of the sardine fishery, nor are stock fluctuations of many present-day MBNMS fisheries well understood. As a second and possibly more important example, we also have little idea how global warming will affect the MBNMS and its oceanography. We nevertheless believe that --- to the extent that knowledge is power --- continued research will be necessary before we can understand and then manage the resources within the MBNMS and beyond. After all, look at all we have learned over the past 20 years!

FIGURES

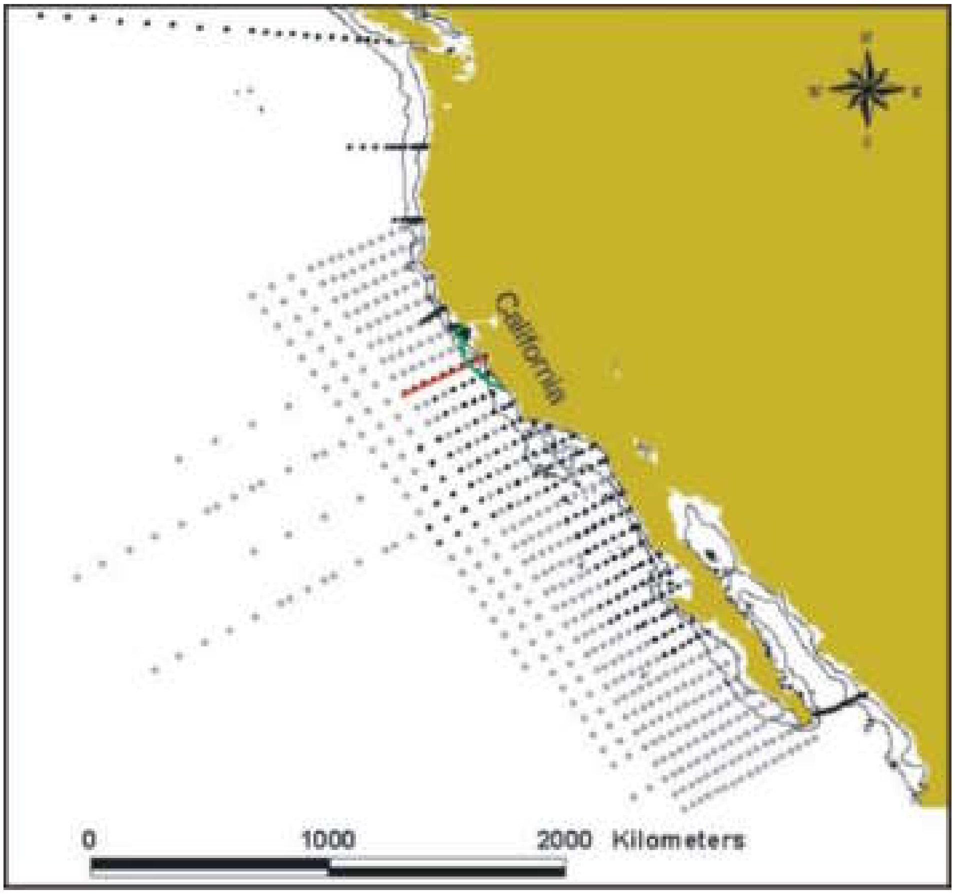

Figure 1. Map of the CalCOFI grid with the MBNMS boundary (green line) and Line 67 (red line) highlighted.

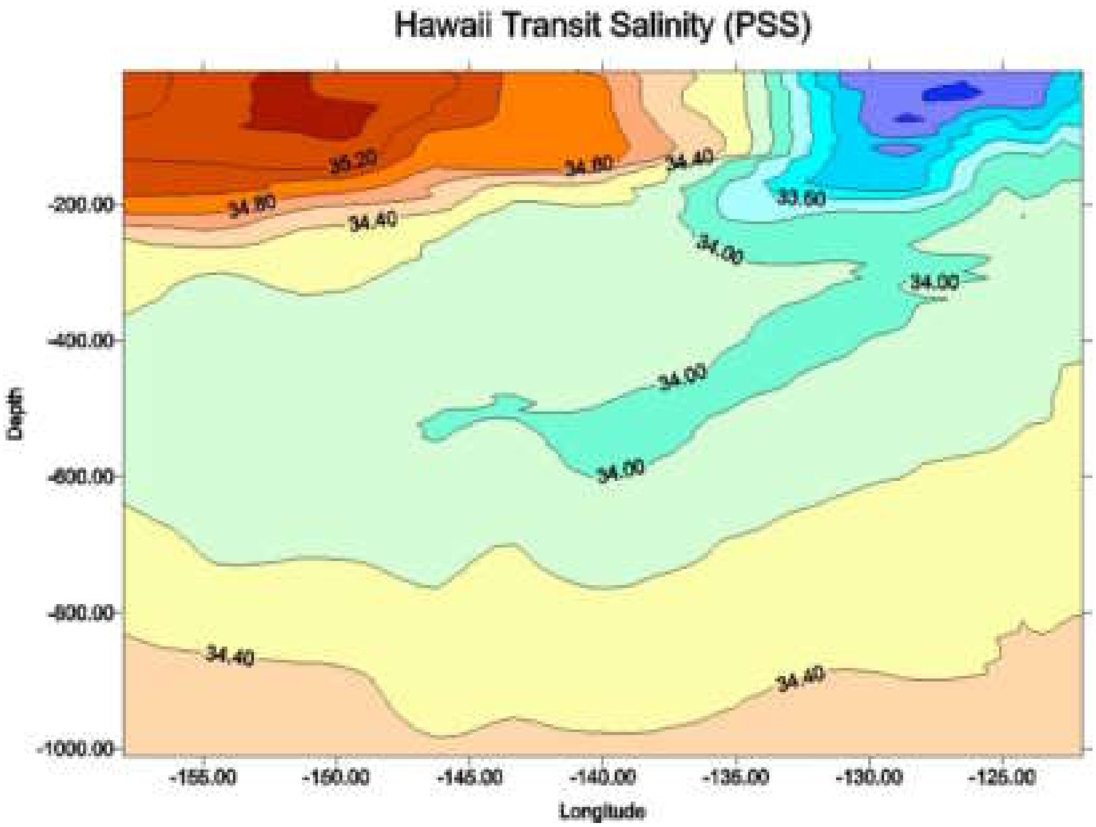

Figure 2. Salinity along a transect across the NE Pacific from Monterey Bay to Hawaii in spring of 2001. On this ‘basin scale’, isolines shoal in the east due to interaction between southward flow of the North Pacific Subtropical Gyre and the earth’s rotation (Coriolis). The California Current is prominent in blue as it flows southward within 1300 km of shore as a fresh surface current (<34 pss; <300 m; 121-135^o W). The core of the CC (~127^o W; ~32.8 pss) is held offshore by isohalines lifted by the gyral circulation and, within ~50 km of shore (<123^o W), by coastal upwelling. Offshore, CC waters grade into the salty (34-36 pss) North Pacific Central Waters shown in red. Both CC and NPC waters are underlain by North Pacific Intermediate Water with a salinity minimum (<34 pss) near 500 m. Despite this salinity inversion, the water column is stable due to warm surface temperature in NPC waters (15-19^o C, temperatures not shown).

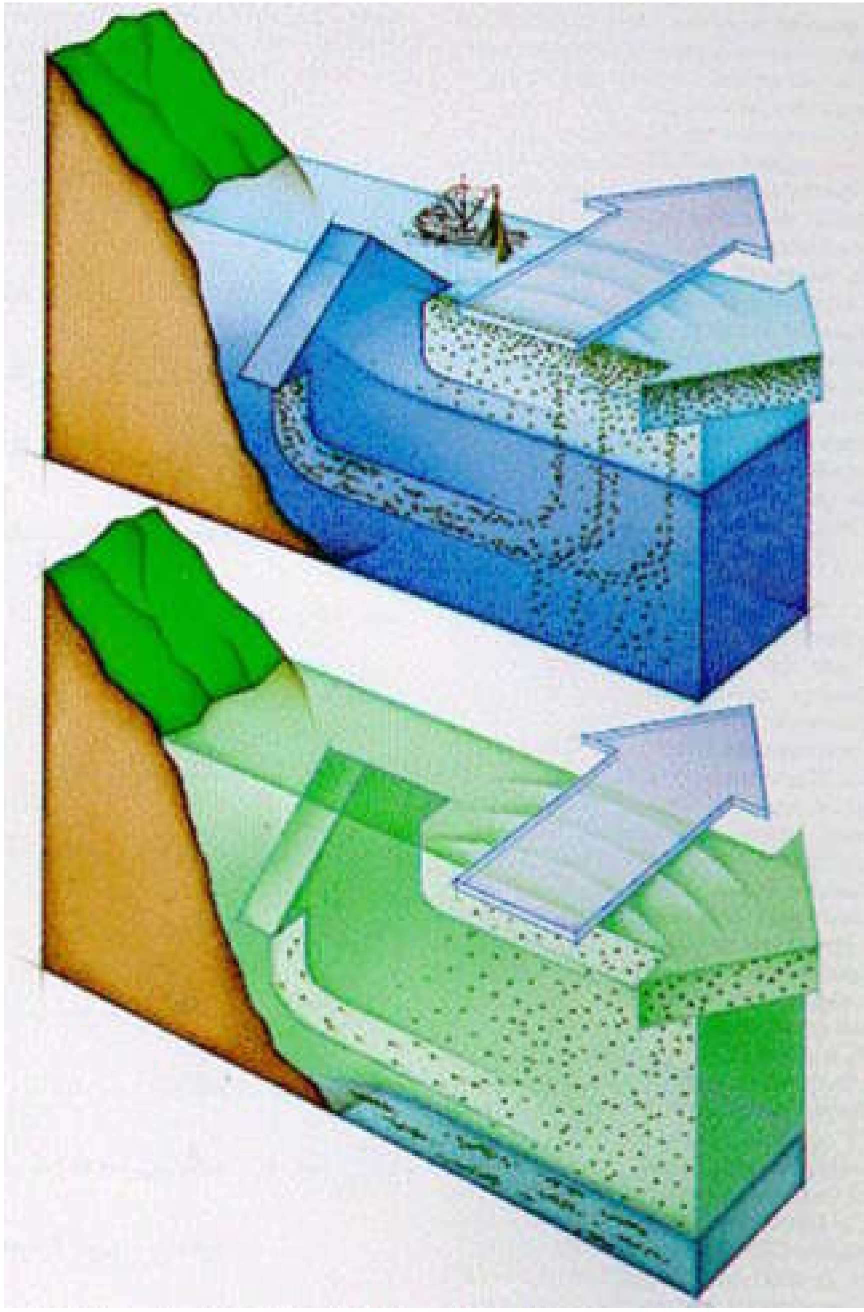

Figure 3. Coastal upwelling schematic, viewed from the north in the northern hemisphere. Equatorward wind and the earth's rotation (Coriolis) interact to drive surface water offshore, causing subsurface water to 'upwell' nearshore (~60 m deep; ~0-50 km offshore at 36^o N). During most years (**top),** the cool and salty upwelled water is also high in plant nutrients, and when exposed to sunlight, phytoplankton growth is stimulated, supporting abundant zooplankton, fish, birds and marine mammal populations. However under unusual conditions such as El Niño (**bottom**), the cool nutrient-rich water is deeper than usual and upwelling does not produce much phytoplankton growth, resulting in animal starvation or migration.

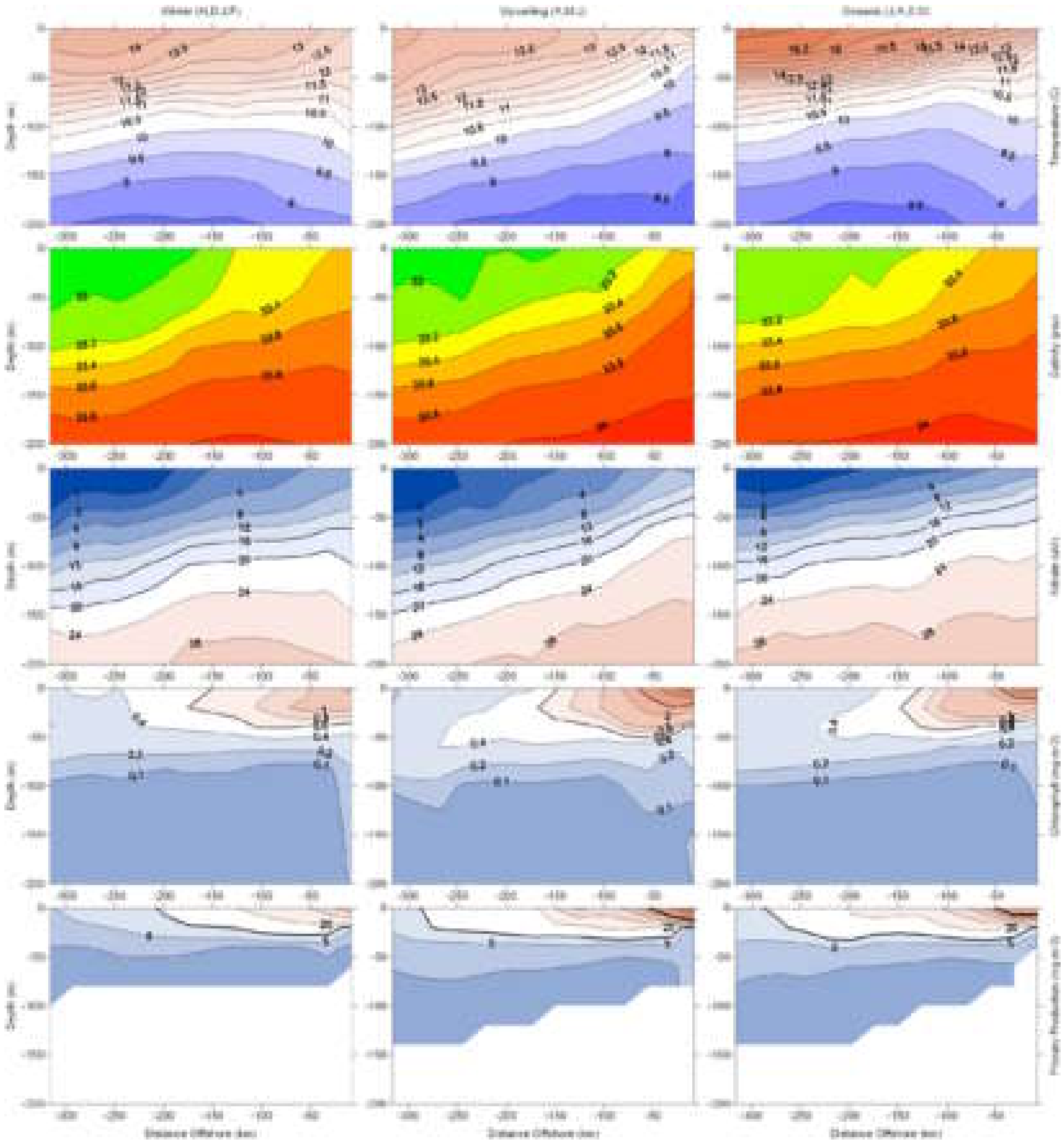

Figure 4. Contours of selected properties during winter non-upwelling (left panels), spring upwelling (middle panels), and fall 'oceanic' months (right panels). Offshore isolines of physical and chemical properties shoal shoreward in all seasons due to equatorward flow of the CC. Nearshore isolines shallower than about 60 m shoal further in spring due to coastal upwelling. Chlorophyll and primary production values are highest near the surface inshore due to intersection of the nutricline with the lighted euphotic zone.

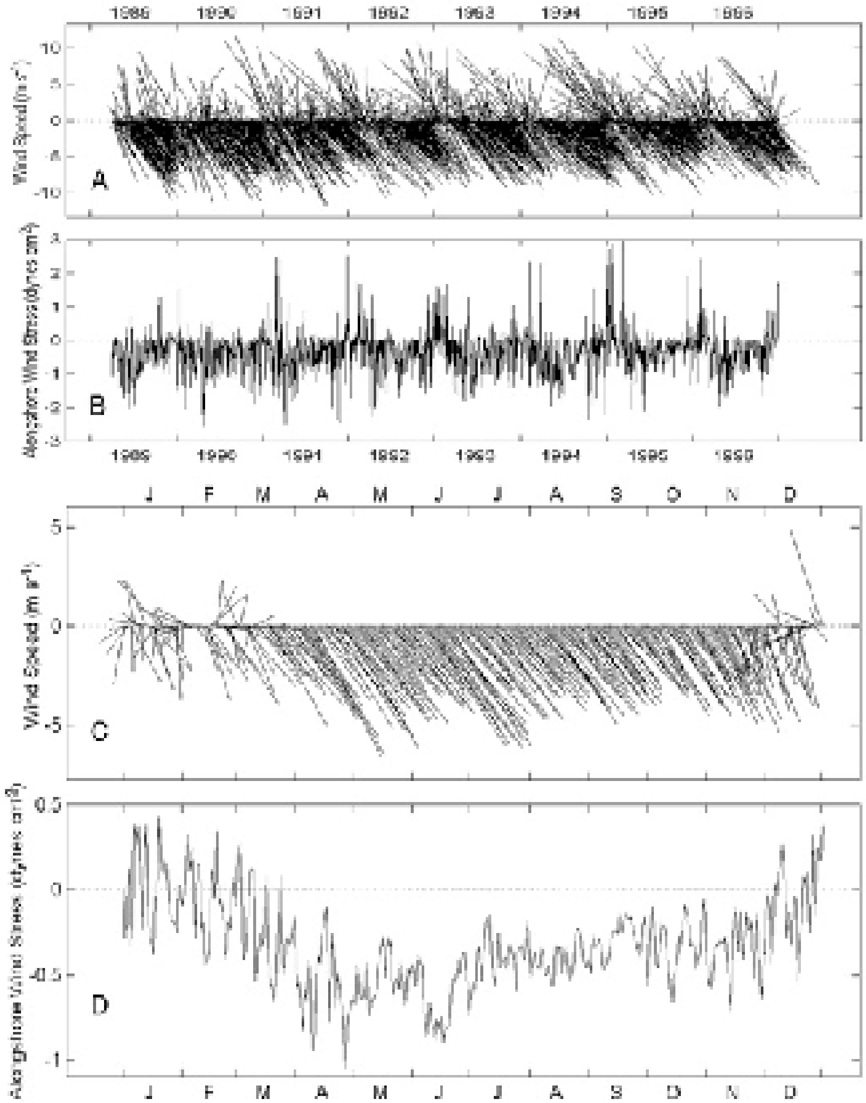

Figure 5. Winds at NDBC buoy 46042 off Monterey Bay, see Figure 12 below for location: (**A**) Daily winds for April 1989 through 1996. Each wind-stick (line) represents the velocity (length of stick) and direction wind blew towards (direction of stick), averaged for one day. Negative values represent southward winds; (**B**) Daily alongshore (150°) wind stress calculated from data in (**A**). Negative values represent southward, upwelling favorable stress; (**C**) Average year of winds at 46042, calculated from data in (**A**); (**D**) Average year of alongshore (150°) wind stress, calculated from data in (**B**).

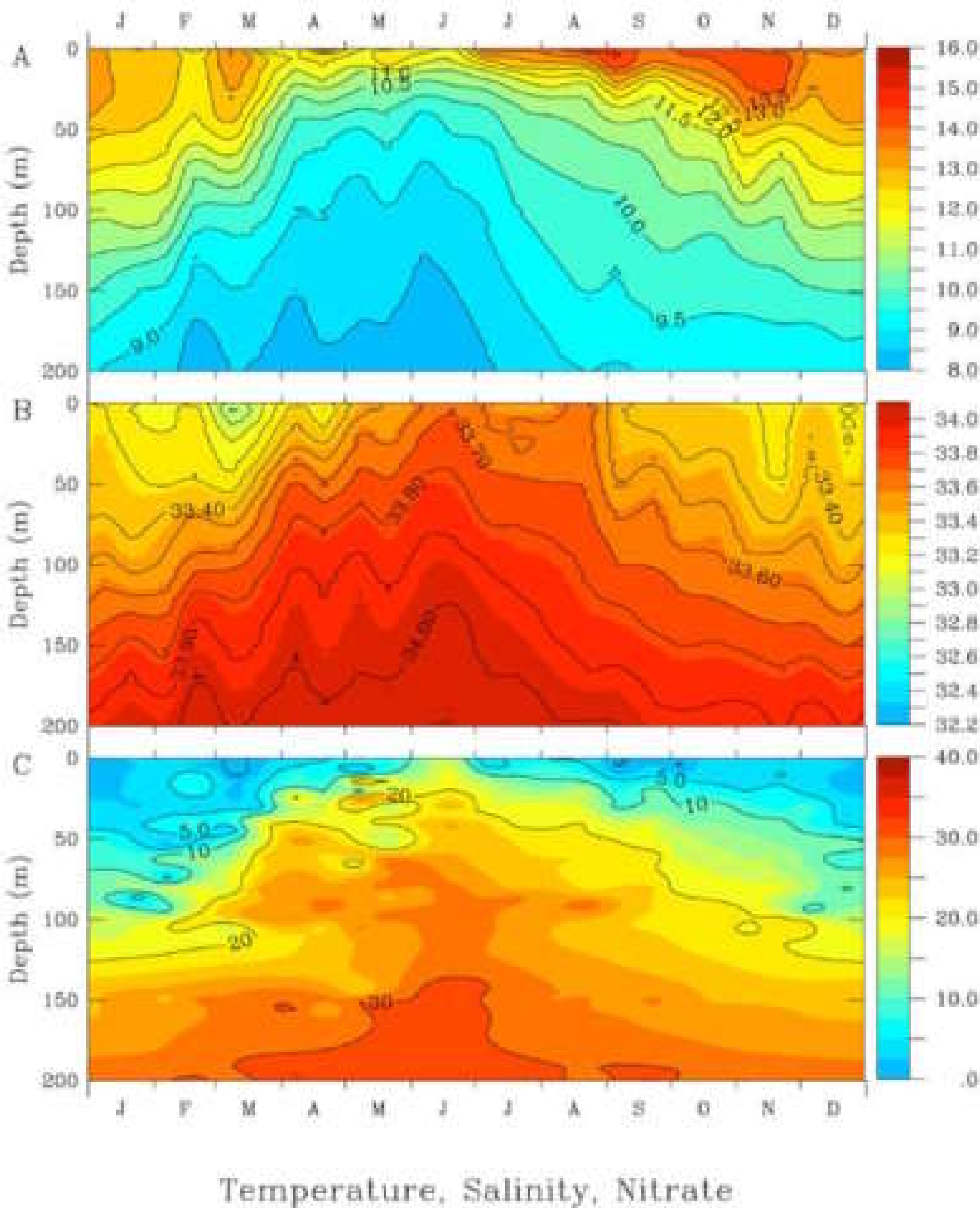

Figure 6. Average year of physical properties to 200 m in central Monterey Bay: (**A**) temperature (°C); (**B**) salinity; and (**C**) nitrate (µM) calculated from the 7.5-yr time series' of Figure 8. Contour lines are: temperature, 0.5 °C intervals; salinity, 0.1 intervals; nitrate lines are 5, 10, 20 and 30 µM.

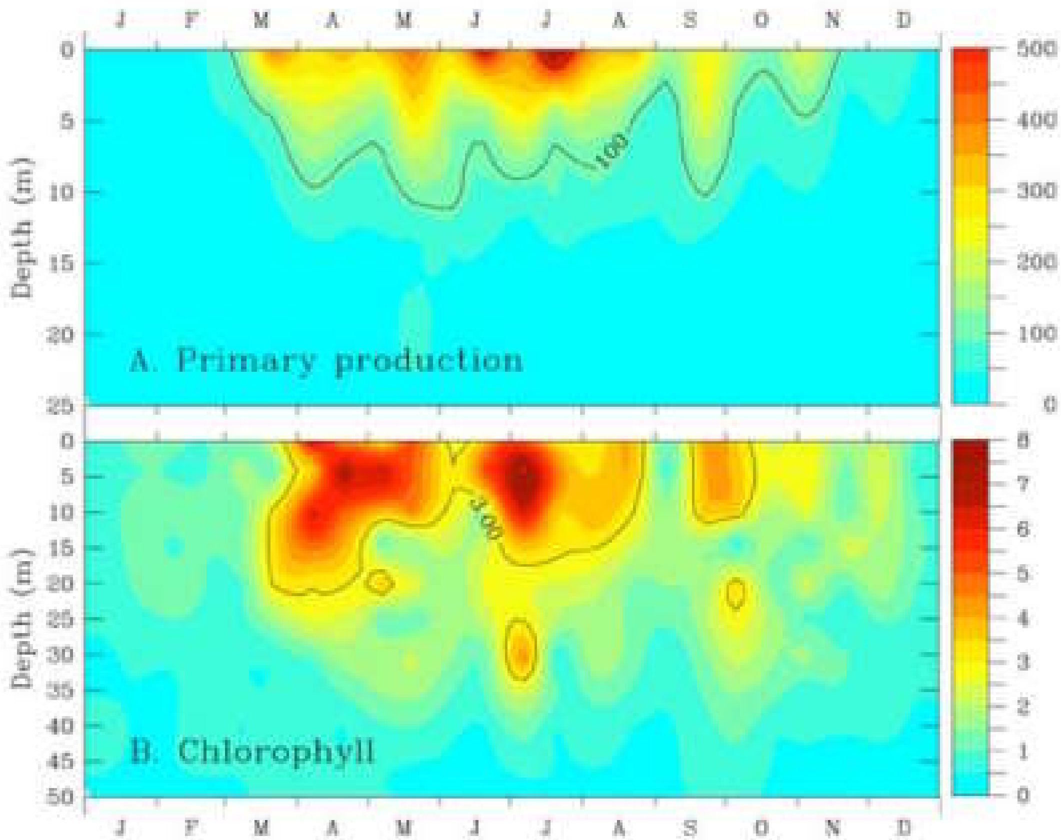

Figure 7. Average year of biological properties in central Monterey Bay calculated from the 7.5-yr time series' of Figure 10: (**A**) primary production to 25 m; and (**B**) chlorophyll to 50 m. Contour lines are: primary production, 100 and 500 mg C m^{-3} da^{-1}; chlorophyll, 2.0 and 6.0 mg chl m^{-3}.

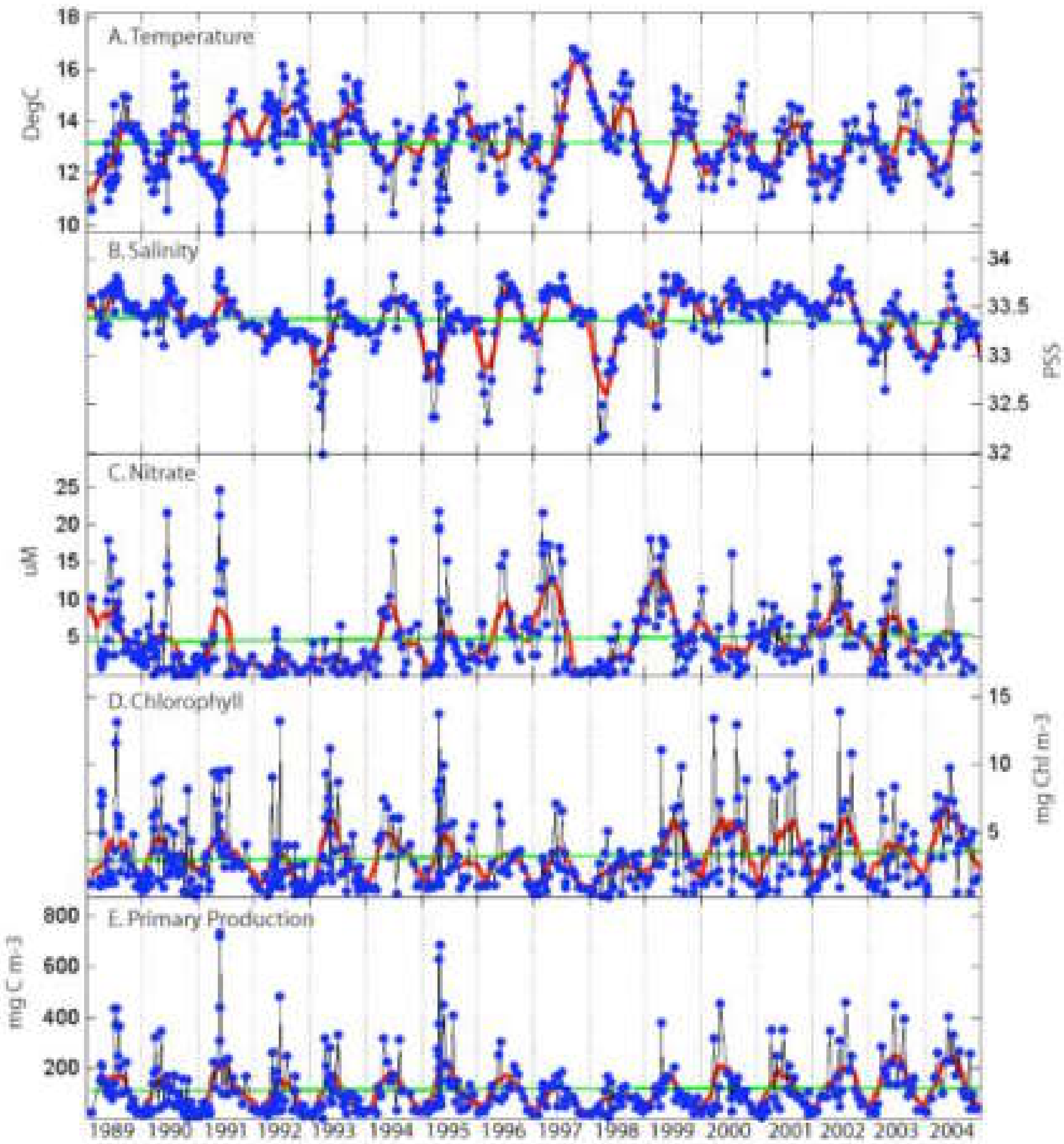

Figure 8. Time series of example parameters (averaged Monterey Bay stations). The series are characterized by strong short-term fluctuations (blue dots), seasonal cycles (red line), interannual fluctuations (red line), and small residual trends (green line). Stations C1, M1 and M2 (see Fig. 12) have been occupied each 2-3 weeks since 1989 (blue dots). Stations offshore of M2 were occupied quarterly from 1988-1991 and again from 1997-2005; data density for these offshore stations is considerably less than shown.

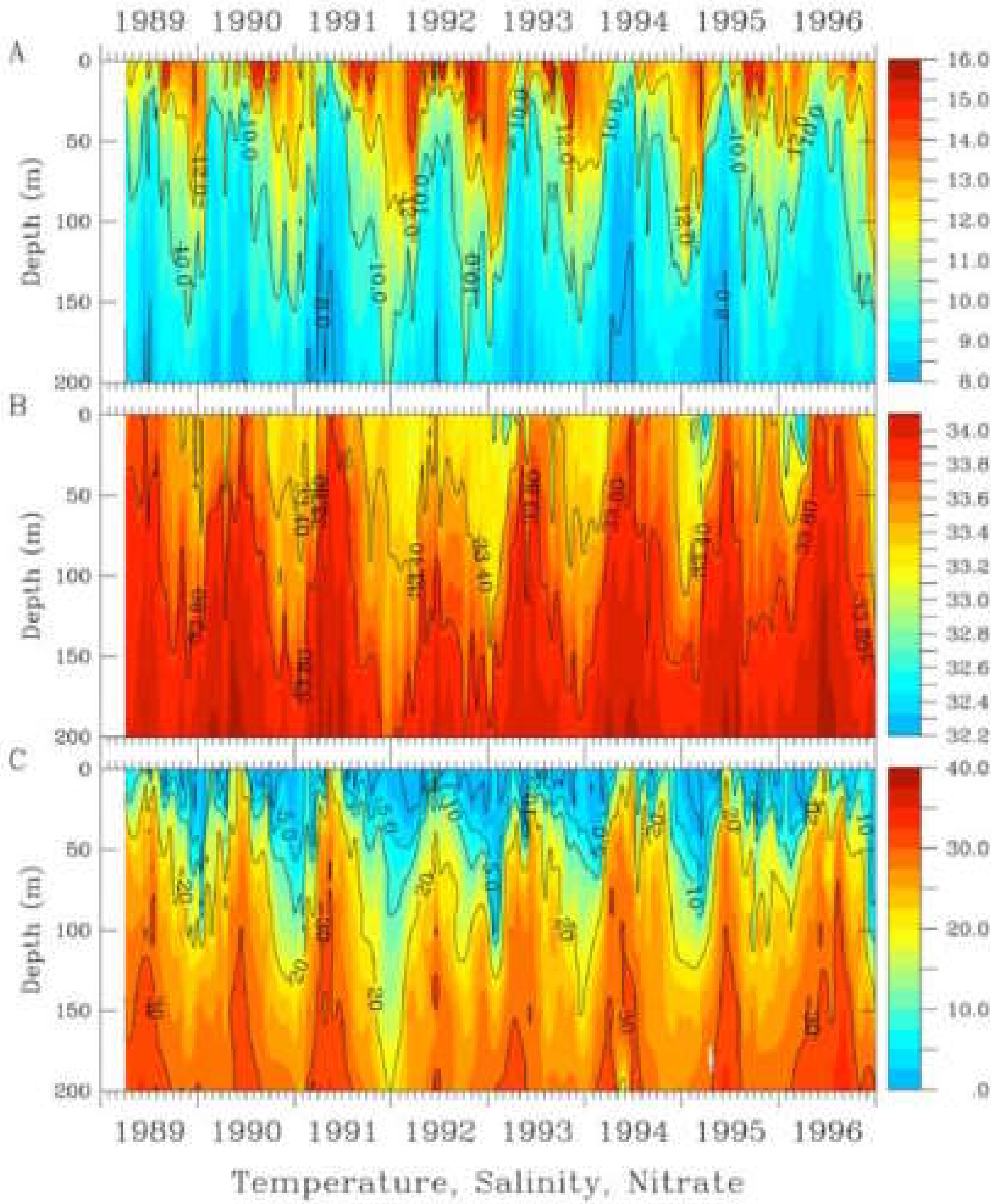

Figure 9. 7.5-yr time series of (A) temperature (°C), (B) salinity, and (C) nitrate (μM) in central Monterey Bay to 200 m. Contour lines are: temperature, 2.0° C intervals; salinity, 0.4 intervals: nitrate lines are 1, 5, 10, 20 and 30 μM.

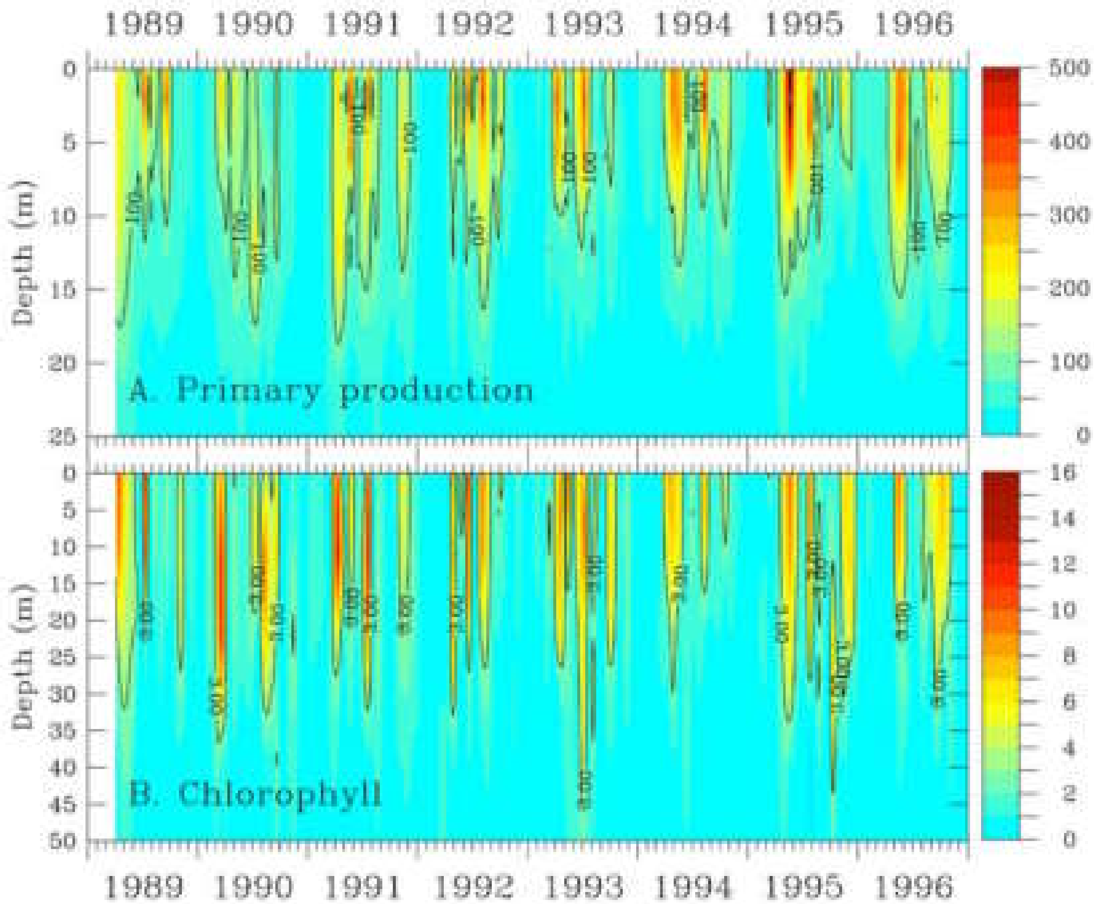

Figure 10. 7.5-yr time series of biological properties in central Monterey Bay: (**A**) primary production to 25 m; and (**B**) chlorophyll to 50 m. Contour lines are primary production, 100 and 500 mg C m^{-3} da^{-1}, and chlorophyll, 2.0 mg chl m^{-3}. Color scale of Figure 10 does not match that of Figure 7.

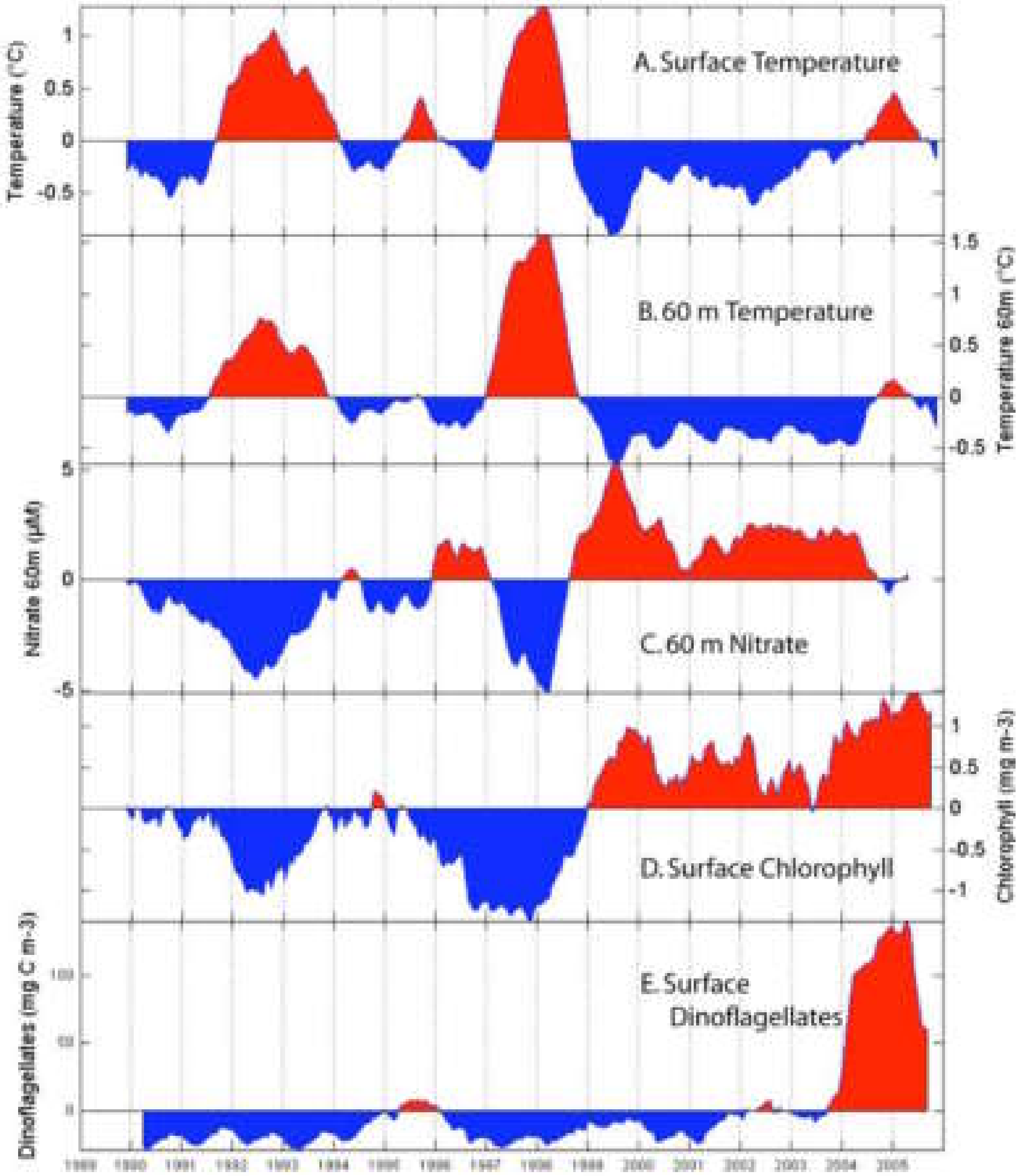

Figure 11. Temperature, nitrate and biological anomalies. The plots above represent deviation from the normal seasonal cycle, with red being high, and blue low. Over 2002-2004, surface temperature (**A**) warmed and dinoflagellate abundance increased (**E**). However, 60 m temperature and nitrate (**B, C**) did not show similar trends nor did overall surface chlorophyll increase (**D**). We speculate that, over this period, remote in-ocean forcing elevated the thermocline and nitrate levels but that lack of local atmospheric forcing permitted the water column to stratify --- conditions known to favor dinoflagellates over other phytoplankton. We continue to monitor these trends but the data for late 2005 and early 2006 are not yet analyzed.

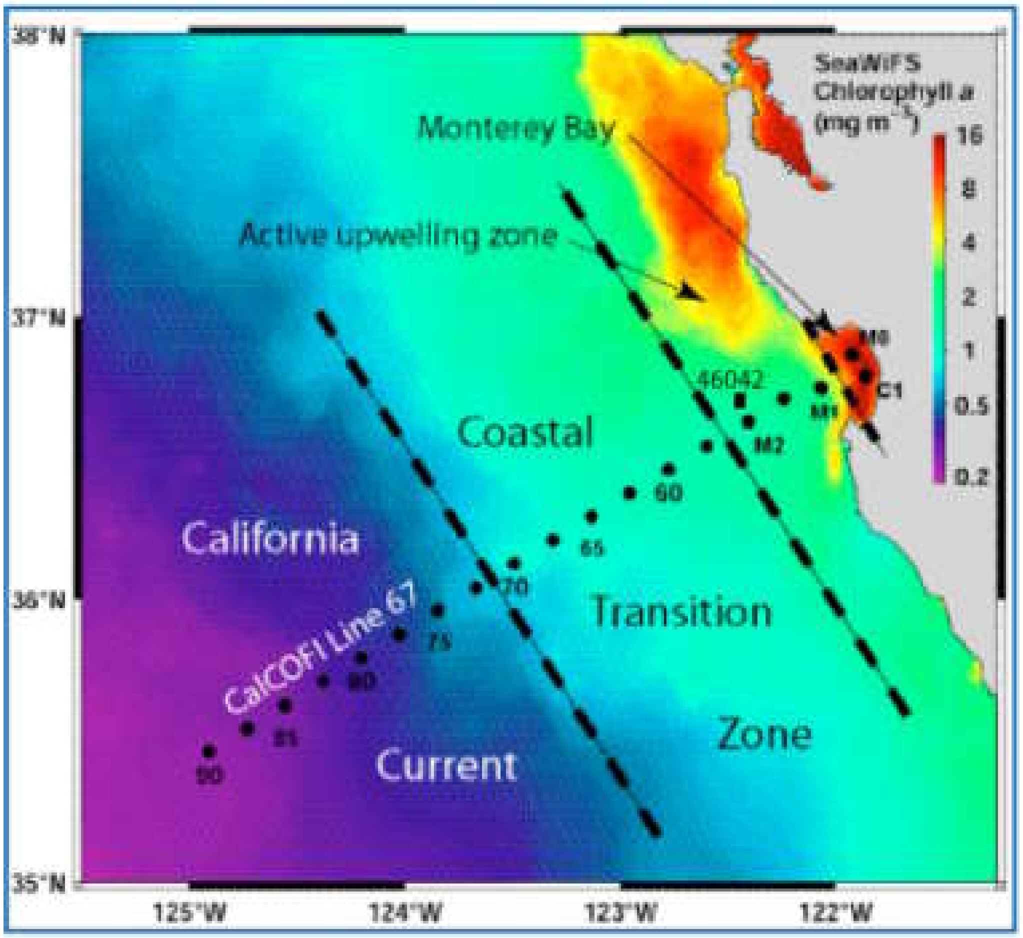

Figure 12. CalCOFI Line 67 off central California, USA, is divided into four hydrographic zones separated by black dashed lines: (1) Monterey Bay (0-20km offshore; Stations C1 and M0); (2) a Coastal Upwelling Zone (one 36° N Rossby Radius broad and 20-52km offshore; Stations M1 to M2, NDBC buoy 46042); (3) the Coastal Transition Zone (52-170km offshore; Stations 60 to 70); and (4) the California Current (170-300km offshore; Stations 75 to 90). The underlying color is an SeaWiFS chlorophyll image (1998-2002).

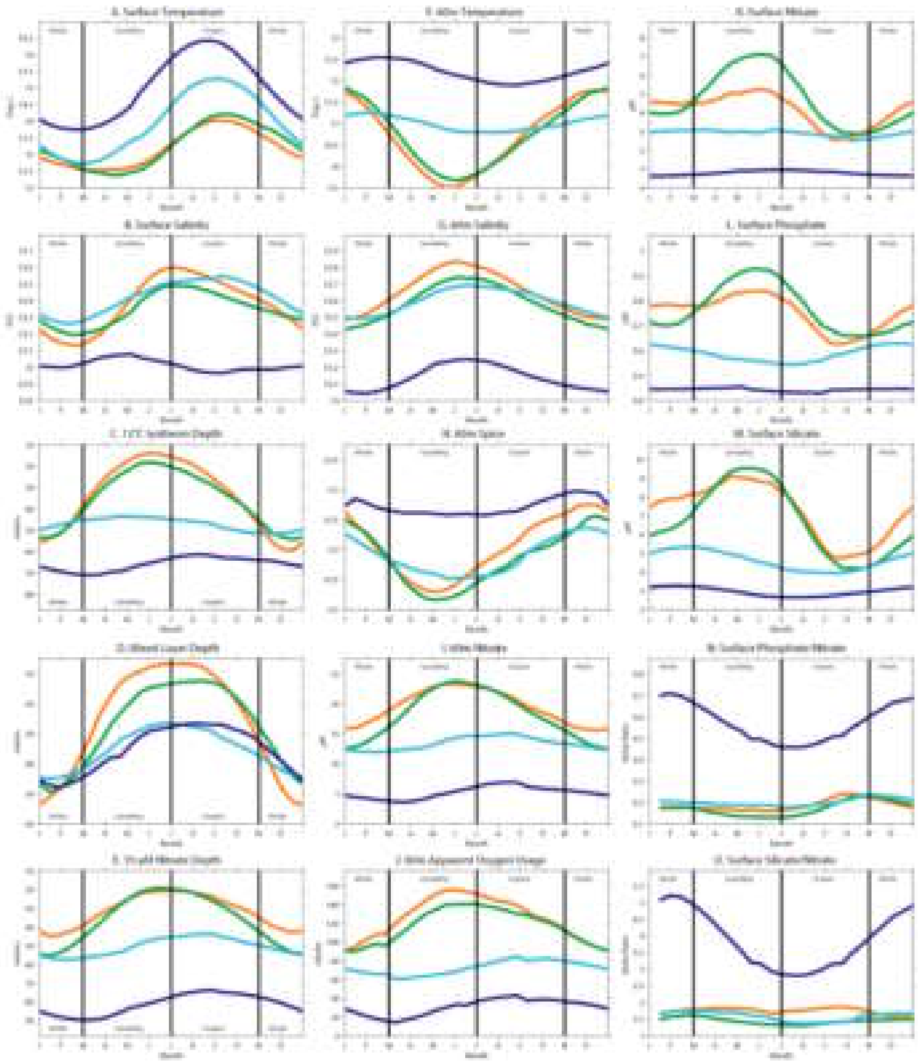

Figure 13. Physical and chemical properties, average annual cycles for Monterey Bay (**MB; orange**), the Coastal Upwelling Zone (**CUZ; green**), the Coastal Transition zone (**CTZ; light blue**), and the California Current (**CC; dark blue**). Raw time series as in Figure 8 were collapsed into a canonical year then smoothed with a 14 day Stineman interpolation followed by a 9 point moving average. The vertical black lines divide the spring upwelling, fall oceanic, and winter inshore countercurrent periods. Surface temperature (**A**) is coldest nearshore and in late winter and warmest offshore and in late summer. 60 m temperature (**F**) is coldest in MB and the CUZ in spring, is intermediate but nearly aseasonal in the CTZ, and high and also aseasonal in the CC. Surface (**B**) and 60 m (**G**) salinity is much lower and less seasonal in the CC than nearshore. 60 m CC spice (**H**) is also nearly aseasonal. Mixed layer depth (**D**) is shallowest in MB and the CUZ in spring, and deep everywhere in winter. The curves for the 12° isotherm (**C**), the 10 µM nitrate isoline (**E**), 60 m nitrate (**I**) and apparent oxygen usage (**J**) are similar in form to inverted curves for 60 m temperature (**F**). The curves for surface nitrate (**K**), phosphate (**L**) and silicate (**M**) are similar with major increases nearshore during late winter and spring, and major drawdown again nearshore but during summer and fall.

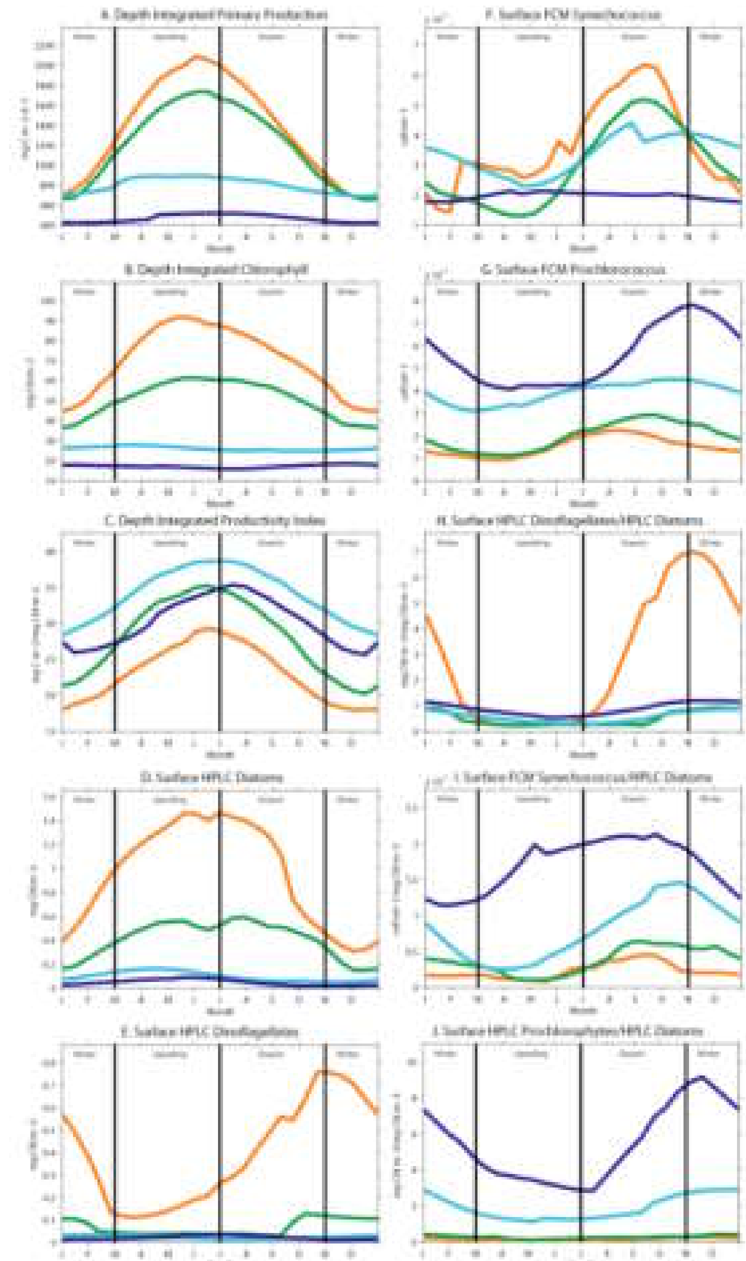

Figure 1. Phytoplankton properties, annual cycles and zones as described under Figure 11. Depth-integrated primary production (**A**) and chlorophyll (**B**) are highest nearshore in MB and the CUZ in spring, and lower and less seasonal offshore in the CTZ and CC. The productivity/biomass ratios (**C**) are, however, all seasonal and lowest in MB. Diatoms (**D**) are most abundant nearshore in spring, whereas dinoflagellates (**E**) are more abundant, also nearshore, in fall and early winter (**H**). The calculated HPLC diatom chlorophyll (D; <1.5 mg m^{-3}) is considerably less than 0 m total chlorophyll determined by fluorescence (not shown; <6 mg m^{-3}). *Synechococcus* (**F**) is most abundant in fall in MB, the CUZ and CTZ, whereas Prochlorococcus (**G**) is most abundant in fall/early winter in the CC. *Prochlorococcus* chlorophyll is more abundant in the CTZ and CC than diatom chlorophyll, especially in winter (**J**).

Appendix 1. CalCOFI and MBARI cruises on L67 from 1949-2006. CalCOFI completed 104 cruises over 49 years, while MBARI completed 64 cruises over 18 years. Since 2003, winter and spring cruises have been joint efforts.

CalCOFI			MBARI		
Cruise Number	**Cruise Name**	**Date**	**Cruise Number**	**Cruise Name**	**Date**
1	4910	Oct-49	105	PP0	Apr-88
2	4911	Nov-49	106	PP1	Aug-88
3	5006	Jun-50	107	PP2	Sep-88
4	5007	Jul-50	108	PP3	Nov-88
5	5008	Aug-50	109	PP4	Feb-89
6	5101	Jan-51	110	PP5	Mar-89
7	5104	Apr-51	111	PP6	May-89
8	5105	May-51	112	PP7	Jul-89
9	5106	Jun-51	113	PP8	Sep-89
10	5107	Jul-51	114	PP9	Nov-89
11	5108	Aug-51	115	PP10	Jan-90
12	5109	Sep-51	116	PP11	Mar-90
13	5109	Sep-51	117	PP12	May-90
14	5111	Nov-51	118	PP13	Jun-90
15	5111	Nov-51	119	PP14	Aug-90
16	5204	Apr-52	120	PP15	Oct-90
17	5205	May-52	121	PP16	Dec-90
18	5206	Jun-52	122	PP17	Feb-91
19	5207	Jul-52	123	S197	Mar-97
20	5208	Aug-52	124	S297	Jun-97
21	5209	Sep-52	125	S397	Jul-97
22	5210	Oct-52	126	S397	Jul-97
23	5211	Nov-52	127	S497	Sep-97
24	5304	Apr-53	128	S198	Jan-98
25	5305	May-53	129	s298	Mar-98
26	5306	Jun-53	130	S398	Apr-98
27	5307	Jul-53	131	S498	May-98
28	5308	Aug-53	132	S598	Aug-98
29	5404	Apr-54	133	S698	Aug-98
30	5405	May-54	134	S798	Nov-98
31	5406	Jun-54	135	S199	Jan-99
32	5407	Jul-54	136	S299	Apr-99
33	5408	Aug-54	137	S399	May-99
34	5506	Jun-55	138	S499	Jul-99
35	5508	Aug-55	139	S599	Nov-99
36	5510	Oct-55	140	S100	Feb-00
37	5604	Apr-56	141	S200	Apr-00
38	5605	May-56	142	S300	Jul-00
39	5707	Jul-57	143	S400	Sep-00
40	5801	Jan-58	144	S500	Dec-00
41	5804	Apr-58	145	S101	Feb-01
42	5807	Jul-58	146	S201	Mar-01
43	5810	Oct-58	147	S301	May-01
44	5810	Oct-58	148	S401	Aug-01
45	5811	Nov-58	149	S501	Dec-01
46	5901	Jan-59	150	s102	Jan-02
47	5904	Apr-59	151	s202	Mar-02
48	5907	Jul-59	152	s302	Jul-02
49	5910	Oct-59	153	s402	Nov-02

50	6001	Jan-60
51	6002	Feb-60
52	6004	Apr-60
53	6009	Sep-60
54	6101	Jan-61
55	6104	Apr-61
56	6107	Jul-61
57	6110	Oct-61
58	6201	Jan-62
59	6203	Mar-62
60	6210	Oct-62
61	6301	Jan-63
62	6304	Apr-63
63	6401	Jan-64
64	6406	Jun-64
65	6501	Jan-65
66	6507	Jul-65
67	6601	Jan-66
68	6607	Jul-66
69	6612	Dec-66
70	6801	Jan-68
71	6806	Jun-68
72	6901	Jan-69
73	6902	Feb-69
74	6902	Feb-69
75	6907	Jul-69
76	6907	Jul-69
77	6908	Aug-69
78	6910	Oct-69
79	6912	Nov-69
80	7201	Jan-72
81	7202	Feb-72
82	7203	Mar-72
83	7207	Jul-72
84	7412	Dec-74
85	7501	Feb-75
86	7503	Feb-75
87	7507	Jul-75
88	7510	Nov-75
89	7801	Jan-78
90	7803	Mar-78
91	7804	Apr-78
92	7805	May-78
93	7807	Jul-78
94	7808	Aug-78
95	8105	Jun-81
96	8106	Jun-81
97	8107	Jul-81
98	8401	Jan-84
99	8402-3	Feb-84
100	8404	Apr-84
101	8405-6	May-84
102	8407	Jul-84
103	8410	Oct-84
104	9804	Apr-98
154	s103	Jan-03
155	s203	Apr-03
156	s303	Jul-03
157	s403	Oct-03
158	s104	Jan-04
159	s204	Apr-04
160	s304	Jun-04
161	s404	Aug-04
162	s504	Oct-04
163	s105	Jan-05
164	s205	Apr-05
165	S305	Jul-05
166	S405	Oct-05
167	s106	Feb-06
168	s206	Apr-06
169	S306	Jul-06