UNIVERSITY OF CALIFORNIA, SAN DIEGO

Climate Impacts on the Planktonic Marine Ecosystem in the Southern California Current

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Oceanography

by

Hey-Jin Kim

Committee in charge:

Arthur J. Miller, Chair
Ivan Evans
Peter J. S. Franks
John A. McGowan
Uwe Send
Lynne D. Talley

2008

The dissertation of Hey-Jin Kim is approved, and it is acceptable in quality and form for publication on microfilm:

Chair

University of California, San Diego

2008

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

ACKNOWLEDGMENTS

I thank Dr. Art Miller, my academic advisor and mentor, who taught me how to enjoy being a scientist. Without his support and encouragement my thesis would not have been finished. He always made my wandering research fun and meaningful. I was lucky to have Art as my adviser.

I thank Professor John McGowan for his support and inspiration as well as for the permission to use his long-term Scripps Pier chlorophyll data. He opened a door for me to the microscopic plankton world. I express my deep gratitude for his pioneering insights and his enthusiasm for understanding nature.

I thank my thesis committee for valuable discussions, comments, and suggestions. I also thank all the scientists and technicians for the Scripps Pier time series and CalCOFI cruises. Lastly, I deeply thank my family and friends for their endless, unconditional support.

Chapter 2 was published in full as Kim, H. –J. and A.J. Miller, Did the thermocline deepen after the 1976-77 climate regime shift in the southern California Current? *Journal of Physical Oceanography*, 2007. This work forms a part of the Ph.D. dissertation of HJK. We gratefully acknowledge funding from DOE (DE-FG02-04ER63857), ONR (N00014-05-1-0363), NASA (NNH04ZYS008N), NSF (ITR OCE01-21332), NOAA (NA17RJ1231 through ECPC and CORC), and California Current Ecosystem LTER (OCE-0417616). The views expressed herein are those of the authors and do not necessarily reflect the views of these agencies. We appreciate many stimulating discussions with John McGowan, Russ Davis and Elizabeth Venrick, as well as the important comments by the two anonymous referees.

Chapter 3 has been submitted in full as Kim, H. –J., A.J. Miller, J.A. McGowan, and M. Carter, Climate and Coastal Algal Blooms in the Southern California Bight, submitted to *Progress in Oceanography*, 2007. This work forms a part of the Ph.D. dissertation of HJK. We gratefully thank all the technicians and scientists for the Scripps Pier time series and CalCOFI cruises. The Pier time series measurement was conducted by Patricia Walker and Connie Fey and was supported in part by a grant from the MacArthur foundation to JM and by CalCOFI. AJM gratefully acknowledges funding from NSF through the California Current Ecosystem LTER (OCE-0417616), NASA (NNG06GC98G), DOE (DE-FG02-04ER63857), ONR (N00014-05-1-0363) and NOAA through the ECPC (NA17RJ1231). The views expressed herein are those of the authors and do not necessarily reflect the views of these agencies.

Chapter 4 has been prepared in full as Kim, H. –J. and A.J. Miller, Decadal variability of density and nitrate, with biological implications, 2008. We gratefully acknowledge funding from NSF through the California Current Ecosystem LTER (OCE-0417616), NOAA through IOOS and ECPC (NA17RJ1231), NASA through MAP (NNG06GC98G), DOE through CCPP (DE-FG02-04ER63857), and ONR through PO (N00014-05-1-0363).

VITA

1998	B.S in Oceanography, Seoul National University, Seoul, Korea
2000	M.S in Oceanography, Seoul National University, Seoul, Korea
2008	Ph.D. in Oceanography, Scripps Institution of Oceanography, University of California, San Diego

PUBLICATIONS

Kim, H-J, A.J. Miller, J. McGowan, and M. Carter, Climate and Coastal Algal Blooms in the Southern California Bight, *Progress in Oceanography*, *sub judice*, 2008.

Kim, H.-J. and A.J. Miller, Did the thermocline deepen in the California Current after the 1976/77 climate regime shift?, *Journal of Physical Oceanography, 37*, 1733-1739, 2007.

Trites, A.W., A.J.Miller, H.D.G. Maschner, M.A. Alexander, S.J. Bograd, J.A. Calder, A. Capotondi, K.O. Coyle, E. Di Lorenzo, B.P. Finney, E.J. Gregr, C.E. Grosch, S.R. Hare, G.L. Hunt, J.Jahncke, N.B. Kachel, H.-J. Kim, C. Ladd, N.J. Mantua, C. Marzban, W. Maslowski, R. Mendelssohn, D.J. Neilson, S.R. Okkonen, J.E. Overland, K.L. Reedy-Maschner, T.C. Royer, F.B. Schwing, J.X.L. Wang and A.J. Winship, Bottom-up forcing and the decline of Steller sea lions in Alaska: Assessing the ocean climate hypothesis, *Fisheries Oceanography, 16*, 46-67, 2007.

Kim, H.-J., Y.-G. Park, and K. Kim, Generation mechanism of near-inertial internal waves observed off the East Coast of Korea, *Continental Shelf Research*, *25*, 1712-1719, 2005.

Miller, A.J., E. Di Lorenzo, D.J. Neilson, H.-J. Kim, A. Capotondi, M.A. Alexander, S.J. Bograd, F.B. Schwing, R. Mendelssohn, K. Hedstrom and D.L. Musgrave, Interdecadal changes in mesoscale eddy variance in the Gulf of Alaska circulation: Possible implications for the Steller sea lion decline, *Atmosphere-Ocean, 43*, 231-240, 2005.

ABSTRACT OF THE DISSERTATION

Climate Impacts on the Planktonic Marine Ecosystem in the Southern California Current

by

Hey-Jin Kim

Doctor of Philosophy in Oceanography
University of California, San Diego, 2008
Arthur J. Miller, Chair

The linkage between physical climate changes and marine ecosystems has been of great interest during recent decades. However, climate-driven primary production changes and their impacts on marine ecosystems over decadal scales are not fully understood. This issue is addressed by analyzing physical-biological changes in the southern California Current (SCC) based on the interdisciplinary datasets of the California Cooperative Fisheries Investigations (CalCOFI) program, Scripps Pier time series, and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) surface chlorophyll.

The 55-year CalCOFI dataset reveals that the upper ocean warmed significantly and the density difference across the thermocline increased in the SCC over decadal scales. This surface-intensified warming results in deepening of the isotherms. However the thermocline depth, defined as the depth with the maximum gradient of temperature, has no significant long-term linear trend. As the surface heating changed the strength of stratification, it also changed the slope of the nitrate-temperature relation for the mid-depth waters (roughly 30 m to 200 m). Thus, the quality of upwelled water may have been fundamentally altered after the shift, which may affect primary production and higher trophic levels.

Algal blooms at the Scripps Pier in the SCC occur with irregular timing and intensity each year. In the 1990's, the algal blooms occurred earlier in the year and with larger amplitudes compared to those of the 1980's. The annual mean Pier chlorophyll concentration exhibits a clear increasing trend with no concomitant trend evident in the Pier SST from 1983 to 2000. The Pier chlorophyll is highly coherent at 3-7 year periods with nearby offshore *in situ* surface chlorophyll observations at CalCOFI station 93.27.

Upper-ocean nitrate concentration has been measured regularly in CalCOFI since 1984, but its variability in earlier CalCOFI decades is not well known. In order to reconstruct nitrate variability in the earlier decades of CalCOFI since 1950, the leading principal component (PC1) of density seasonal anomalies is used as a quantitative proxy for nitrate since the first principal component (PC1) of upper-ocean density is correlated with the upper-ocean nitrate content. The nitrate proxy PC1 provides a new perspective on the bottom-up forcing of the long-term changes in macrozooplankton observed in CalCOFI. The nitrate proxy decreases from 1950 to the early 1990's, but increases afterwards, which is a tendency that is similar to that exhibited by the surface chlorophyll and displacement volume macrozooplankton biomass time series in CalCOFI, supporting the idea that bottom-up forcing by the physical climate system drives changes in the plankton biomass.

Chapter 1 Introduction

During recent decades unusual climate changes have occurred, but their impacts on marine ecosystems are not fully understood. Long-term variability in the ocean is particularly important because many physical ocean variables such as sea surface temperature (SST) are dominated by low frequency changes [*Davis*, 1976]. In this study, physical-biological climate changes in the southern California Current (CC) are examined on a wide range of time scales from seasonal to inter-decadal using *in situ* observations of the California Cooperative Fisheries Investigations (CalCOFI) data and the Scripps Pier time series, remotely sensed chlorophyll data derived from Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and simulated data from the Regional Ocean Modeling System (ROMS) to address these questions: 1) What stratification changes are observed in the 57-year CalCOFI dataset and how are they related to nutrient supply to the euphotic zone on decadal time scales? 2) How do oceanic climate changes interact with planktonic marine ecosystems in the southern CC? Can we detect biological changes at coastal waters in recent decades? Are they correlated with climate changes? 3) What are the physical processes that induce spring blooms in the southern CC?

Many observations show substantial climate changes in the California Current System (CCS) in recent decades, *e.g.,* surface intensified warming and strengthened stratification [*Roemmich and McGowan*, 1995; *Bograd and Lynn*, 2003; *Kim and Miller*, 2007], sea level rise [*Roemmich*, 1992], and circulation pattern changes [*Bograd and Lynn*, 2003; *Lentz and Chapman*, 2004]. These physical climate changes in the southern portion of the California Current (hereinafter SCC) have been prominently observed in the multidisciplinary dataset of CalCOFI program. However, it is important to determine to what extent we can identify biological changes as a response to these physical climate changes on decadal timescales.

The CC ecosystem clearly responds to physical climate changes [*Chelton et al.*, 1982; *Abbott and Barksdale*, 1991; *Bakun and Nelson*, 1991; *McGowan et al.*, 1998; *Bograd and Lynn*, 2001; *McGowan et al.*, 2003; *Di Lorenzo et al.*, 2005; *Hsieh et al.*, 2008]. *Abbott and Barksdale [1991]* show that wind forcing is coupled with phytoplankton distributions in the central CC. Ocean temperature and chlorophyll concentration in the CCS are linked to equatorial El Niño/Southern Oscillation (ENSO) events [*Bograd and Lynn*, 2001; *Chavez et al.*, 2002], although the linkage appears only if the ENSO signal is strong like 1982-83 El Niño and 1997-1999 El Niño/La Niña events [*Kim et al.*, 2008]. A geographic boundary of vertically migrating open ocean fish moved to the north due to upper-ocean warming in the Southern California Bight (SCB) [*Hsieh et al.*, 2008].

The fundamental level of the complicated food web in marine ecosystems is photosynthetic phytoplankton [*Doney*, 2006]. There are two limiting factors for photosynthesis: sunlight and nutrients. But the two essentials for primary production come from the opposite direction; sunlight is the strongest at the surface and decreases exponentially with depth. However nutrients increase with depth and they are often depleted within the 1% light level, which is roughly 30-70 m from the surface in the CalCOFI domain. Therefore certain physical processes are required to push up the dense nutrient-rich water to the shallow euphotic zone from the lower layer of the ocean for photosynthesis. The CC is well known as an coastal upwelling-driven ecosystem [*Bakun and Nelson*, 1991; *Winant and Dorman*, 1997; *Pickett and Paduan*, 2003]. However, offshore Ekman pumping induced by positive wind stress curl drives an equivalent amount of upwelling in the SCC [*Pickett and Paduan*, 2003]. The amount of upwelled water has a strong seasonality [*Winant and Dorman*, 1997], and changes from year to year. Climate changes, e.g. upper ocean warming and stratification changes, might alter the upwelling intensity. However, it is still an open question how climate changes during recent decades affect the amount of nutrient supply into the euphotic zone, primary production, and higher trophic levels of marine ecosystems. Addressing this issue can offer a better understanding of the 70% decrease of macrozooplankton biomass found by Roemmich and McGowan [1995].

Roemmich and McGowan [1995] show surface intensified warming and a 70% decrease of macrozooplankton biomass from 1950 to 1993 using the CalCOFI dataset. They suggested that the climatic warming and consequently stronger stratification of the upper-ocean might suppress the upwelling cell and reduce the nutrient supply, which might result in reduced primary production and the macrozooplankton decline. However, climate forcing of primary production in the CCS over decadal time scales is not fully understood because of the sparseness of data. Thus, identifying a long-term trend in chlorophyll is essential to better understanding of a possible link between climatic warming and the zooplankton decrease. This issue will be addressed by quantifying stratification strength over decadal time scales in terms of thermocline and pycnocline changes in Chapter 2.

It is still an open question how primary production responds to the recent decadal climate changes. Due to the limitation of coastal data, characteristics of very nearshore chlorophyll variation and the relationship between nearshore chlorophyll measurements and broader-scale patterns observed offshore have remained unclear. This issue can offer an understanding of physical-biological characteristics and long-term marine ecosystem changes in the SCC.

A few previous studies detected long-term trends of regional and global primary production [*Gregg and Conkright*, 2002; *Antoine et al.*, 2005; *Behrenfeld et al.*, 2006]. However they analyzed satellite-derived (Coastal Ocean Color Scanner (CZCS), and SeaWiFS) surface chlorophyll data, which contain significant error in the nearshore ocean where most primary production occurs. Therefore, long-term chlorophyll variability in the nearshore will be analyzed using the 18-year Scripps Pier time series and related to the offshore CalCOFI dataset in Chapter 2 and Chapter 3.

One of most prominent features of the CC ecosystem is a high chlorophyll concentration along a narrow coastal band with a width approximately 50 km from the coast [*Strub et al.*, 1990; *Legaard and Thomas*, 2006]. The narrow coastal band is the area where most primary production occurs, and coastal upwelling is considered to be the driving mechanism that brings nutrients upward in the CCS although the Southern California Bight (SCB) has a weak seasonality compared to other CCS regions.

The seasonal changes of alongshore wind stress and wind stress curl force upper ocean isopycnal deepening and shoaling in the SCC, which might cause nutrient level changes as well. *Winant and Dorman* [1997] show that seasonal isopycnal changes are associated with seasonal wind stress patterns using the CalCOFI dataset. However, nitrate patterns corresponding to these isopycnal changes have not been analyzed. Moreover interannual variability of the isopycnal seasonal anomalies has not been identified in the SCB although there have been several studies analyzing shoaling or deepening of nutricline depth with one-dimensional vertical nitrate profiles [*McGowan et al.*, 2003; *Rykaczewski and Checkley*, 2008].

The seasonality of density and nitrate sections will be examined and associated with wind stress, and then the temporal variability over decadal time scales of depth-longitude sections of density and nitrate seasonal anomalies will be detected by empirical orthogonal function (EOF) analysis using the 57-year CalCOFI dataset in Chapter 4. The upper-ocean responses of isopycnals and iso-nitrate contours to wind stress curl pattern might be associated with basin-scale wind stress changes. Thus two climate indices, the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997; *Chavez et al.*, 2002; *Mantua and Hare*, 2002; *Peterson and Schwing*, 2003] and the North Pacific Gyre Oscillation (NPGO) [*Di Lorenzo et al.*, 2008], will be compared to the seasonal density anomaly changes. Biological implications of those low frequency density and nitrate changes will be discussed. Spatial patterns of surface chlorophyll will be also analyzed by EOF analysis using daily SeaWiFS images. A numerical modeling study is introduced to understand the oceanic response of nitrate flux to climatological wind stress.

.

.

References

Abbott, M.R., and B. Barksdale, Phytoplankton Pigment Patterns and Wind Forcing Off Central California, *Journal of Geophysical Research-Oceans*, *96* (C8), 14649-14667, 1991.

Antoine, D., A. Morel, H.R. Gordon, V.F. Banzon, and R.H. Evans, Bridging ocean color observations of the 1980s and 2000s in search of long-term trends, *Journal of Geophysical Research-Oceans*, *110* (C6), 2005.

Bakun, A., and C.S. Nelson, The Seasonal Cycle of Wind-Stress Curl in Subtropical Eastern Boundary Current Regions, *Journal of Physical Oceanography*, *21* (12), 1815-1834, 1991.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, Climate-driven trends in contemporary ocean productivity, *Nature*, *444* (7120), 752-755, 2006.

Bograd, S.J., and R.J. Lynn, Physical-biological coupling in the California Current during the 1997-99 El Niño-La Niña cycle, *Geophysical Research Letters*, *28* (2), 275-278, 2001.

Bograd, S.J., and R.J. Lynn, Long-term variability in the Southern California Current System, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2355-2370, 2003.

Chavez, F.P., J.T. Pennington, C.G. Castro, J.P. Ryan, R.P. Michisaki, B. Schlining, P. Walz, K.R. Buck, A. McFadyen, and C.A. Collins, Biological and chemical consequences of the 1997-1998 El Niño in central California waters, *Progress in Oceanography*, *54* (1-4), 205-232, 2002.

Chelton, D.B., P.A. Bernal, and J.A. Mcgowan, Large-Scale Interannual Physical and Biological Interaction in the California Current, *Journal of Marine Research*, *40* (4), 1095-1125, 1982.

Davis, R.E., Predictability of Sea-Surface Temperature and Sea-Level Pressure Anomalies over North Pacific Ocean, *Journal of Physical Oceanography*, *6* (3), 249-266, 1976.

Di Lorenzo, E., A.J. Miller, N. Schneider, and J.C. McWilliams, The warming of the California current system: Dynamics and ecosystem implications, *Journal of Physical Oceanography*, *35* (3), 336-362, 2005.

Di Lorenzo, E., N. Schneider, K.M.Cobb, P.J.S. Franks, K. Chhak, A.J. Miller, J.C.McWilliams, S.J.Bograd, H.Arango, E. Curchitser, T.M.Powell, and P.Riviere, North Pacific Gyre Oscillation Links Ocean Climate and Ecosystem Change, *Geophysical Research Letters*, 2008.

Doney, S.C., Oceanography - Plankton in a warmer world, *Nature*, *444* (7120), 695-696, 2006.

Gregg, W.W., and M.E. Conkright, Decadal changes in global ocean chlorophyll, *Geophysical Research Letters*, *29* (15), 2002.

Hsieh, C.H., H.-J. Kim, W. Watson, and E. Di Lorenzo, Climate-driven changes in abundance and distribution or larvae of oceanic fishes in the southern California region, *in preparation*, 2008.

Kim, H.-J., and A.J. Miller, Did the Thermocline Deepen in the California Current after the 1976/77 Climate Regime Shift?, *Journal of Physical Oceanography*, *37* (6), 1733-1739, 2007.

Kim, H.-J., A.J. Miller, J. McGowan, and M. Carter, Climate and coastal algal blooms in the Southern California Bight, *Progress in Oceanography*, *sub judice*, 2008.

Legaard, K.R., and A.C. Thomas, Spatial patterns in seasonal and interannual variability of chlorophyll and sea surface temperature in the California Current, *Journal of Geophysical Research-Oceans*, *111* (C06032), doi:10.1029/2005JC003282, 2006.

Lentz, S.J., and D.C. Chapman, The importance of Nonlinear cross-shelf momentum flux during wind-driven coastal upwelling, *Journal of Physical Oceanography*, *34* (11), 2444-2457, 2004.

Mantua, N.J., and S.R. Hare, The Pacific decadal oscillation, *Journal of Oceanography*, *58* (1), 35-44, 2002.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bulletin of the American Meteorological Society*, *78* (6), 1069-1079, 1997.

McGowan, J.A., S.J. Bograd, R.J. Lynn, and A.J. Miller, The biological response to the 1977 regime shift in the California Current, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2567-2582, 2003.

McGowan, J.A., D.R. Cayan, and L.M. Dorman, Climate-ocean variability and ecosystem response in the northeast Pacific, *Science*, *281* (5374), 210-217, 1998.

Peterson, W.T., and F.B. Schwing, A new climate regime in northeast pacific ecosystems, *Geophysical Research Letters*, *30* (17), 2003.

Pickett, M.H., and J.D. Paduan, Ekman transport and pumping in the California Current based on the U.S. Navy's high-resolution atmospheric model (COAMPS), *Journal of Geophysical Research-Oceans*, *108* (C10), 2003.

Roemmich, D., Ocean Warming and Sea-Level Rise Along the Southwest United-States Coast, *Science*, *257* (5068), 373-375, 1992.

Roemmich, D., and J. McGowan, Climatic Warming and the Decline of Zooplankton in the California Current, *Science*, *267* (5202), 1324-1326, 1995.

Rykaczewski, R.R., and D.M. Checkley, Jr, Influence of ocean winds on the pelagic ecosystem in upwelling regions, 10.1073/pnas.0711777105, *Proceedings of the National Academy of Sciences*, *105* (6), 1965-1970, 2008.

Strub, P.T., C. James, A.C. Thomas, and M.R. Abbott, Seasonal and Nonseasonal Variability of Satellite-Derived Surface Pigment Concentration in the California Current, *Journal of Geophysical Research-Oceans*, *95* (C7), 11501-11530, 1990.

Winant, C.D., and C.E. Dorman, Seasonal patterns of surface wind stress and heat flux over the Southern California Bight, *Journal of Geophysical Research-Oceans*, *102* (C3), 5641-5653, 1997.

Chapter 2 Decadal thermocline changes

ABSTRACT

The 55-year CalCOFI dataset in the southern California Current reveals a significant surface-intensified warming and stratification (buoyancy frequency) change across the 1976-77 climate regime shift. However, the average depth of the thermocline, defined as the maximum gradient of temperature, did not change significantly across the regime shift. The maximum-gradient criterion for thermocline depth may be more appropriate than following an isotherm because the isotherm necessarily deepens in the presence of surface-intensified warming. As the surface heating changed the strength of stratification, it also changed the slope of the nitrate-temperature relation for the mid-depth waters (roughly 30 m to 200 m). Thus, the quality of upwelled water may have been fundamentally altered after the shift.

2.1 Introduction

The California Current System (CCS) is highly variable and very productive. Many physical features, e.g., stratification (Bograd and Lynn, 2003; McGowan et al., 2003), coastal upwelling (Huyer, 1983), mesoscale eddies (Davis, 1985; Hickey, 1998), cold filaments (Strub et al., 1991) etc., occur over various temporal and spatial scales, interacting with the marine ecosystem. Long-term changes of the biological response to physical climate forcing are of great interest, because the nonlinear ecosystem may not be linearly related to persistent environmental disturbances (Hsieh et al., 2005).

Roemmich and McGowan (1995, hereinafter RM95) identified a 70% decrease of macrozooplankton biomass and 1^{o}C upper ocean warming from 1951 to 1993 in the CalCOFI (California Cooperative Oceanic Fisheries Investigations) *in situ* dataset for the southern part of the CCS. They suggested that increased stratification caused less nutrient input to the upper ocean and decreased new production, which is a possible reason for the decrease of zooplankton biomass.

It is still unclear whether this is a secular trend, possibly due to greenhouse warming, or a transient signal associated with Pacific decadal variability (Mantua et al., 1997). Although the data length is not long enough to separate these two signals, the CalCOFI upper-ocean temperature is highly correlated with basin-scale climate regime shifts in 1976-77 and 1998-99 (Miller et al., 1994; Hayward et al., 1999; Peterson and Schwing, 2003, Fig. 1). Interannual variations are also strong, with several large peaks of warm temperature in El-Nino years (1957-58, 1983-84, and 1997-98). The long-term warming of the upper ocean temperature appears to decrease after 1998 (Fig. 1), which could be an interannual anomaly or the start of a new cooler climate regime. Since the

1998-99 climate regime shift is still controversial, we focus here on only the 1976-77 climate regime shift with the cold regime defined as 1950 to 1977 and the warm regime as 1977 to 1998.

Previous studies of the 1976-77 shift (Bograd and Lynn, 2003; McGowan et al., 2003; Di Lorenzo et al., 2005) all describe this warming and attempt to quantify a deepening of the thermocline after the shift. RM95 show that averaged temperature sections of line 80 and 90 (Fig. 2) manifest surface warming up to 1^{o}C. The warming signature penetrates below 200 m, which is well below the thermocline. Bograd and Lynn (2003) use temperature harmonics calculated with the CalCOFI dataset to estimate that the average depth of the thermocline (defined as the 12^{o}C isotherm) increased from 64 m to 76 m. Di Lorenzo *et al*. (2005) use objective maps of the 26.4 sigma-t isopycnal depth, which varies between 180 m and 220 m, as a proxy of the thermocline in CalCOFI to show that it deepened by 18 m after the 1976-77 shift. Both of these definitions of the thermocline reflect the upper ocean warming but not the stratification changes of the water column structure.

Notice that defining thermocline depth based on isothermal depth or isopycnal depth will inevitably result in a deepening after surface intensified warming. This definition does not adequately represent the structural change in the *stratification* of the water column. In this note, we examine long-term stratification changes in terms of the thermocline (pycnocline), defined as the depth with maximum vertical temperature (density) gradient, and the buoyancy frequency. The maximum gradient definition can provide a more direct link to the nutrient flux associated with the ecosystem response. This is similar to the approach of Palacios et al. (2004) who use a vertical gradient criterion for thermocline depth to find coastal deepening and offshore shoaling of the thermocline in the CCS. However, they use state-spaced analyzed WOD98 records from 1950-1993 in eight CCS locations while we analyze raw data from the 1950 – 2004 CalCOFI dataset, yielding higher spatial coverage and resolution in the southern CCS.

We ask the fundamental question: Did the thermocline deepen in the southern California Current after the 1976-77 climate regime shift? The answer is then related to possible changes in nutrient fluxes and their biological implications. The CalCOFI program and the data used in this study are briefly introduced in section 2, and observed stratification changes are shown quantitatively in section 3. These results and their biological implications are discussed in the last section.

2.2 Data

CalCOFI is a unique ongoing program to support long-term observations in the Southern California Bight. Temperature and salinity have been measured since 1949. These 29,682 profiles are sampled at the standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, and 500 m). The key period around the climate regime shift in 1976-1977, however, does not have many samplings. Moreover, nutrient measurements have been routinely collected only since 1984 (Venrick, 1998). The current CalCOFI cruise domain has 66 stations (Fig. 2), which have been repeated quarterly since 1984. The data analysis in this study is limited to these 66 nominal stations (11,744 profiles for each variable) to minimize spatial aliasing, and each profile was interpolated by a piecewise cubic spline method (Akima, 1970) to obtain 1 m vertical resolution.

Stratification is quantified using four variables: thermocline depth (D_{thermo}), pycnocline depth (D_{pycno}), thermocline temperature (T_{thermo}), and maximum buoyancy frequency (N_{max}). D_{thermo} (D_{pycno}) is calculated for each profile as the depth with the maximum vertical gradient of temperature (density). T_{thermo} is defined as the temperature at D_{thermo}, and N_{max} is calculated from the density profile. Notice that N_{max} occurs at D_{pycno}. Monthly mean climatologies are computed for each station and subtracted from each station's time series because variances differ greatly among stations in CalCOFI dataset, *i.e.* a domain average is not appropriate for representing every station.

Both D_{thermo} and D_{pycno} tend to be shallower at inshore stations than offshore stations. This motivates dividing the 66 CalCOFI stations into two groups, "inshore" and "offshore" groups. Hayward and Venrick (1998) defined inshore and offshore CalCOFI regimes according to key physical-biological features. In the inshore regime, chlorophyll concentrations are high, and pycnocline and nutricline are shallow, and vice versa in the offshore regime. We examine stratification changes for very similar inshore and offshore station groupings, roughly corresponding to the shelf region and deep-water region of CalCOFI.

2.3 Results

The anomalies of D_{thermo} (Fig. 3a) and D_{pycno} (Fig. 3b) are dominated by decadal variations of alternating positive (deepening) and negative (shoaling) values. No clear evidence of a climate regime shift occurs in these plots for any of the CalCOFI lines. Time series of D_{thermo} and D_{pycno} were additionally examined for each station (figures not shown), and they also reveal no significant trend. Objectively mapped monthly CalCOFI data (Di Lorenzo et al. 2005) show results consistent with Fig. 3a,b (figures not shown) as well. Means of the probability density functions (PDFs) of these D_{thermo} and D_{pycno} anomalies also have no significant differences between the cool regime and the warm regime, even when the grouping the observations into inshore (Figure 4, left panels) and offshore (Figure 4, right panels) stations.

In contrast, T_{thermo} anomalies (Fig. 3c) are persistently negative in the cool regimes while they retain the positive signs in the warm regime. PDFs of the T_{thermo} anomalies (Fig. 4c) also clearly indicate the shift to the warm regime in 1976-77 with a significant mean change of about 1^{o}C. Note that the warming signal in Figs. 3c and 4c is not simply a result of the strong El Nino events occurring after 1976-77. The number of data observed during the 1997-98 El Nino period is 186, which occupies only 3% of all the data for the warm regime from 1977 to 1998. The surface intensified warming rendered the upper ocean more stable after the 1976-77 shift as indicated by the significantly higher N_{max} values (Fig. 3d, 4d).

The thermocline depth is often used as a proxy for nutricline depth (Bograd and Lynn, 2003; McGowan et al., 2003) because of the lack of nutrient data. Nitrate is the important limiting factor for the primary production in the California Current. We therefore examine whether changes occurred in the well-known nitrate-temperature negative relationship across the regime shift. Nitrate has 4818 profiles from 1977 to 1998, however unfortunately it was rarely sampled before the 1977 climate regime shift (193 samplings), with even fewer sampling locations within the current CalCOFI grid (151 samplings). We therefore focused on the four stations, 80.60, 80.80, 90.37, and

90.60, that have the highest samplings (Fig. 2). Fig. 5 shows the nitrate-temperature relationship for station 90.37 (the circle on line 90, closer to the coast) before and after the 1976-77 shift, which is representative of all four stations. There are four nitrate profiles measured at station 90.37 in two winter cruises before the 1976-77 shift, and nitrate was sampled almost every year from 1983 to 1997 (22 winter profiles). Only winter (Jan-Mar) observations are used because the nitrate sampling is the highest in winter before the shift and it characterizes the important antecedent ocean conditions to the upwelling season.

The nitrate-temperature relation shows an important change after the 1976-77 climate regime shift (Fig. 5). The nitrate-temperature relation for the mid-depth waters, from roughly 30m to 200m, changes slope across the shift. In the mid-depth waters, higher values of nitrate for a given temperature occur after the shift because of the upper ocean warming. The deep waters (>200m) and surface waters (<30m), in contrast, do not exhibit any significant changes in their temperature-nitrate relationship. This is because the deep water was not directly affected by the surface heating and because surface waters are dominated by biological uptake of nitrate, which occurs on time scales much shorter than long-term variations of upwelling.

2.4 Discussion

A detailed analysis of the raw 55-year CalCOFI data confirms that thermocline temperature, T_{thermo}, warms after the 1976-77 climate regime shift (Fig. 3c,4c). But the analysis clearly reveals that the thermocline depth, D_{thermo}, remains essentially constant across the regime shift (Fig. 3a,4a), although it does vary on decadal timescales. The surface intensified warming after the 1976-77 shift (Fig. 1) resulted in an increased temperature difference across the thermocline, a higher buoyancy frequency, N_{max} (Fig. 3d,4d), and a more stable upper ocean.

Palacios et al. (2004) suggested that the coastal thermocline deepened while the offshore thermocline shoaled for key stations throughout the California Current after the 1976-77 shift. However, within the CalCOFI grid (Fig. 2), two of their four stations (locations 1 and 4 in Fig. 2) show no significant trend in their state-space analysis. A higher resolution analysis, using all the CalCOFI station data, results in no significant change in thermocline depth across the shift, even when grouping stations into coastal and offshore regions (Fig. 4a,b). Furthermore, our results are not sensitive to the specific choice s for the time intervals of the regimes.

Roemmich and McGowan (1995) suggested that the surface warming increased the temperature difference across the thermocline resulting in less lifting of the thermocline by the coastal upwelling. Both thermocline depth and stratification strength (the buoyancy frequency at the pycnocline) affect the nutrient flux due to coastal upwelling because they influence the source of upwelled water. As the surface heating changed the strength of stratification, it also changed the slope of the nitrate-temperature relation (Fig. 5) for the mid-depth waters (roughly 30m to 200m). The 12°C isotherm, which many previous studies have used as a proxy of thermocline depth, is associated with increased nitrate values after the shift. But since the stratification also increased, the depth from which upwelled waters are mixed to the surface may have changed. Further study is needed to determine how these changes might have interacted to affect circulation, upwelling, mixing and nutrient fluxes to the euphotic zone. The temperature-nitrate relationship of the mid-depth waters may be a key indicator of the quality of upwelled water that contributes to sustaining primary production in the euphotic zone.

2.5 Acknowledgements

This work forms a part of the Ph.D. dissertation of HJK. We gratefully acknowledge funding from DOE (DE-FG02-04ER63857), ONR (N00014-05-1-0363), NASA (NNH04ZYS008N), NSF (ITR OCE01-21332), NOAA (NA17RJ1231 through ECPC and CORC), and California Current Ecosystem LTER (OCE-0417616). The views expressed herein are those of the authors and do not necessarily reflect the views of these agencies. We appreciate many stimulating discussions with John McGowan, Russ Davis and Elizabeth Venrick, as well as the important comments by the two anonymous referees.

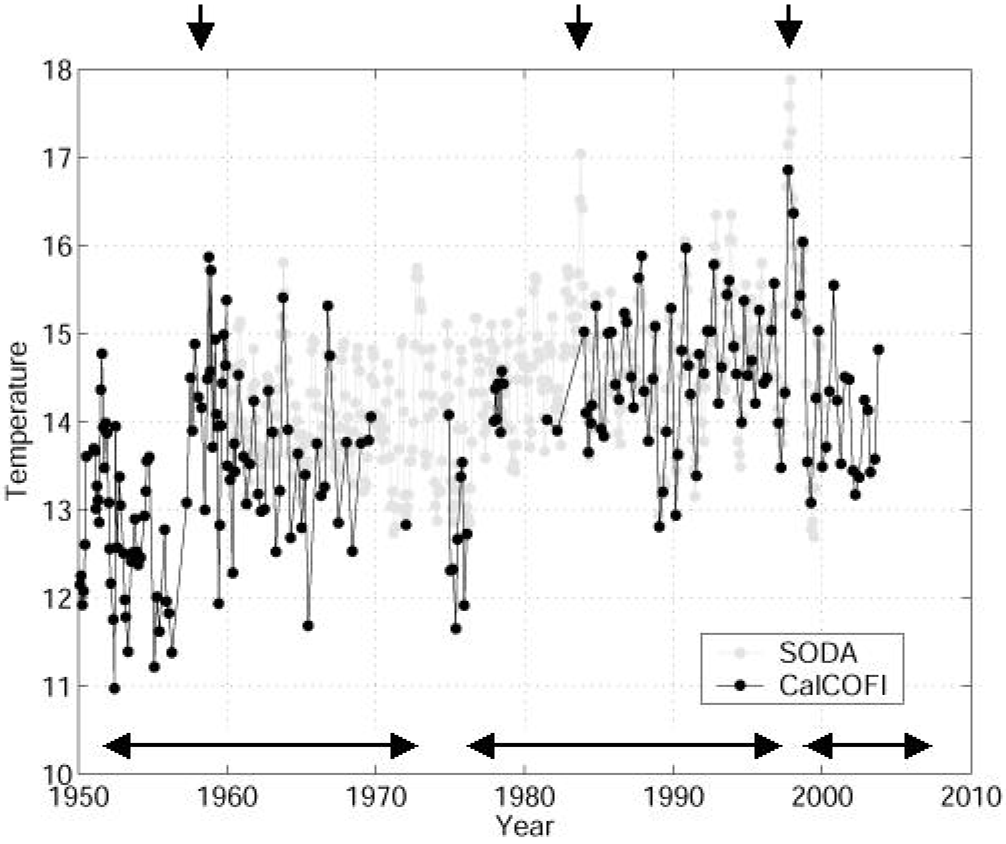


Fig. 2.1. The upper ocean temperature average from the surface to 100 m depth along the line 80. The black dots are calculated with the CalCOFI observations, and the gray dots are from SODA (Simple Ocean Data Assimilation, courtesy by Benjamin Giese, Texas A & M). SODA dataset was resampled as the same stations of the line80. Red arrows above the plot represent El Nino year (1957-58, 1982-83, and 1997-98), and orange arrows below the plot indicate different climate regime periods (cold regime from 1950 to 1976, warm regime from 1977 to 1998)

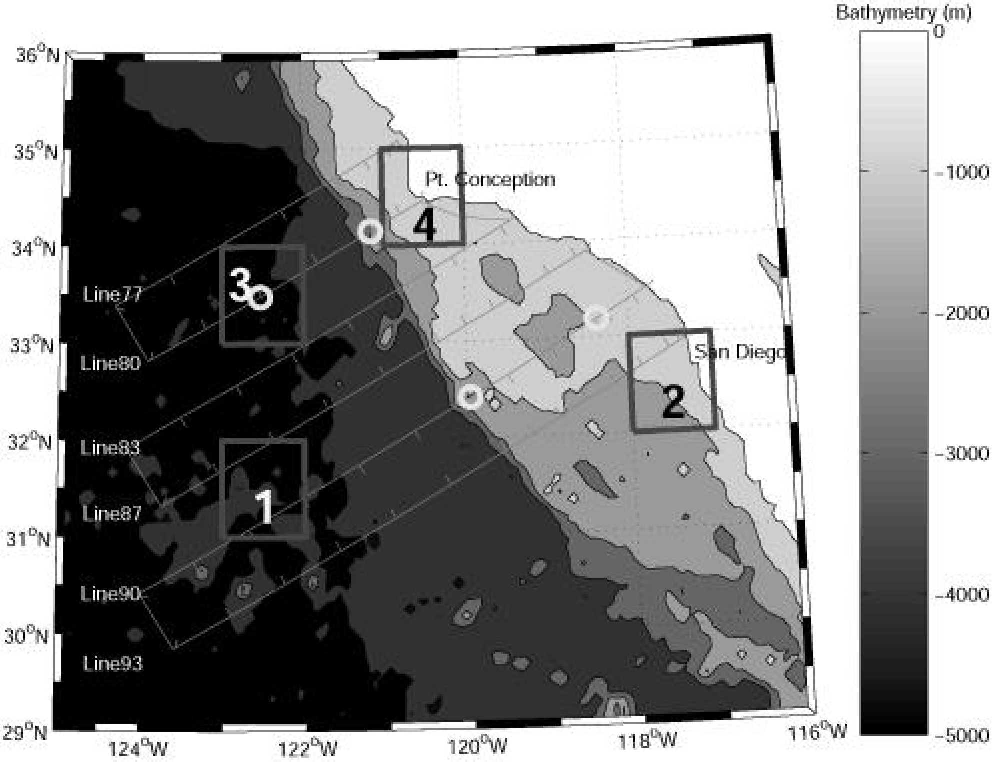


Fig. 2.2. The current station map of CalCOFI observations (http://www.calcofi.org). Boxes with numbers represent four of the eight locations studied by Palacios *et al.* (2004). Four circles are the locations with the most NO_3 measurements before 1976. Inshore group includes 36 stations landward from the 2000 m bathymetry, and the rest of 66 CalCOFI stations are offshore group.

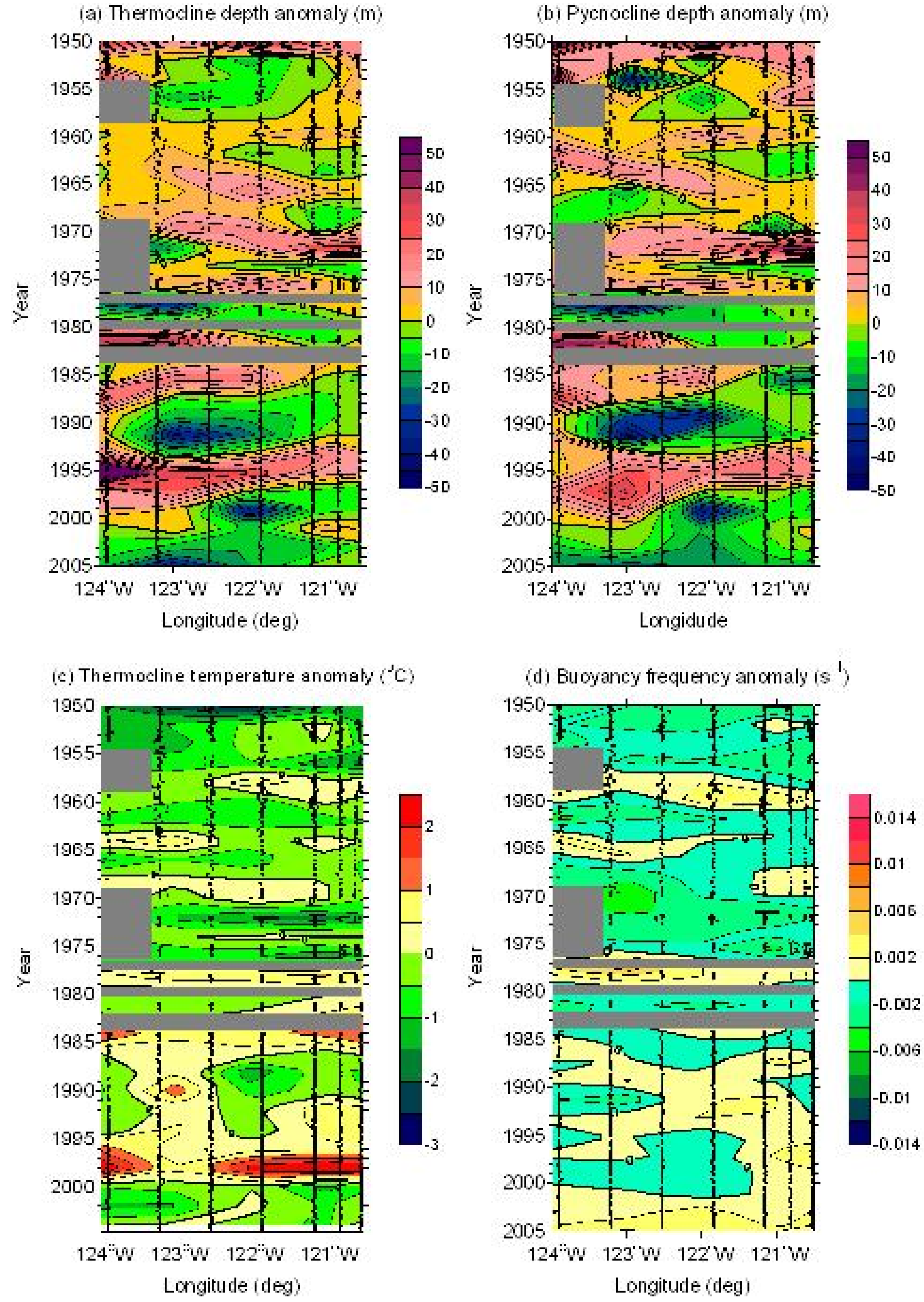


Fig. 2.3. Hovmoller diagrams for Line 80 thermocline anomalies (a), pycnocline anomalies (b), thermocline temperature anomalies (c), and buoyancy frequency anomalies at the pycnocline (d). All the nominal lines in the CalCOFI grid (Fig. 2.2) showed similar patterns.

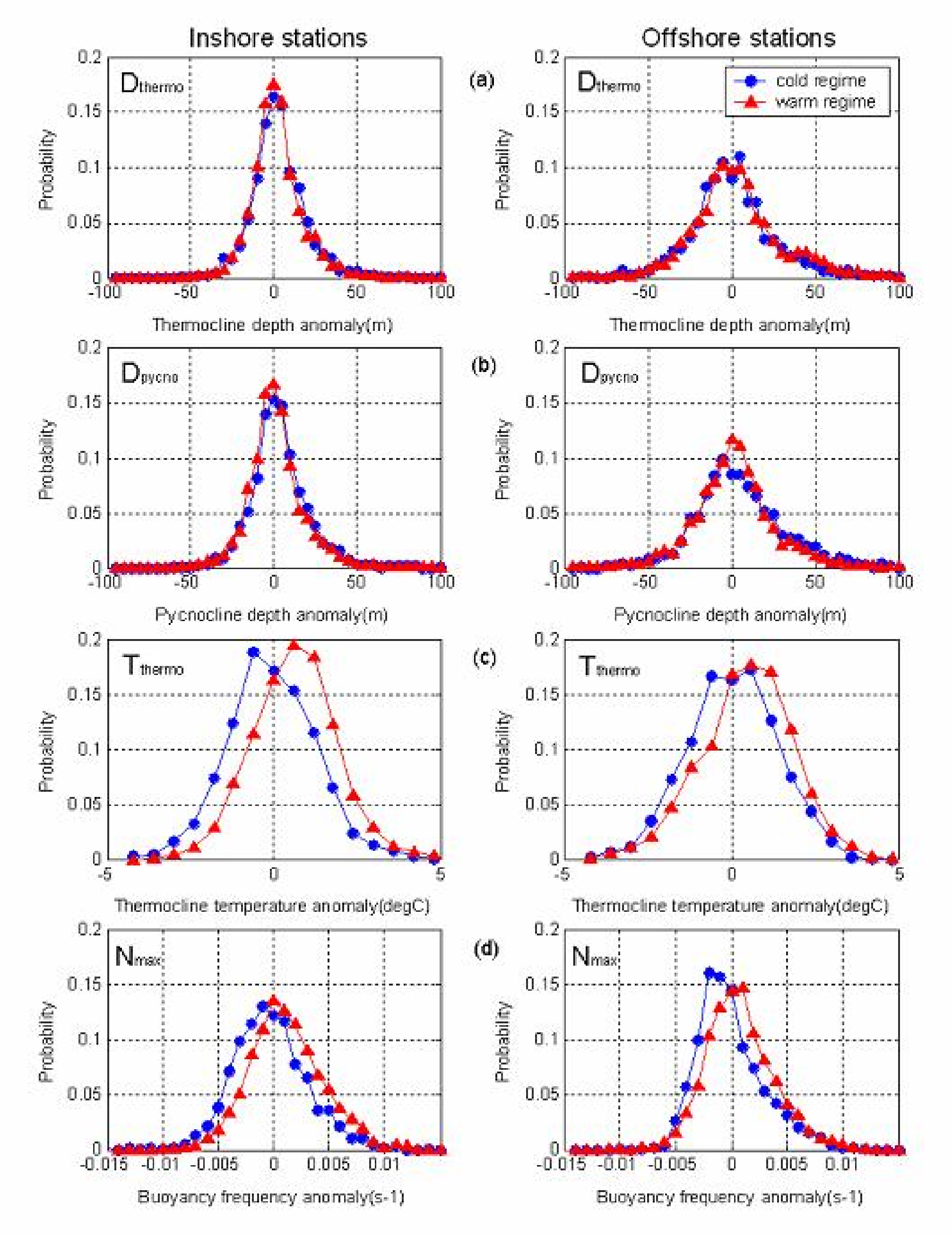


Fig. 2.4. Probability density functions (PDFs) of the four variables as in Fig. 2.3. Left panels are coastal stations (Fig. 2.2), and right panels are offshore stations (Fig. 2.2). Red lines represent for the cool regime (1950 – 1976) and blue lines represent for the warm regime (1977 – 1998).

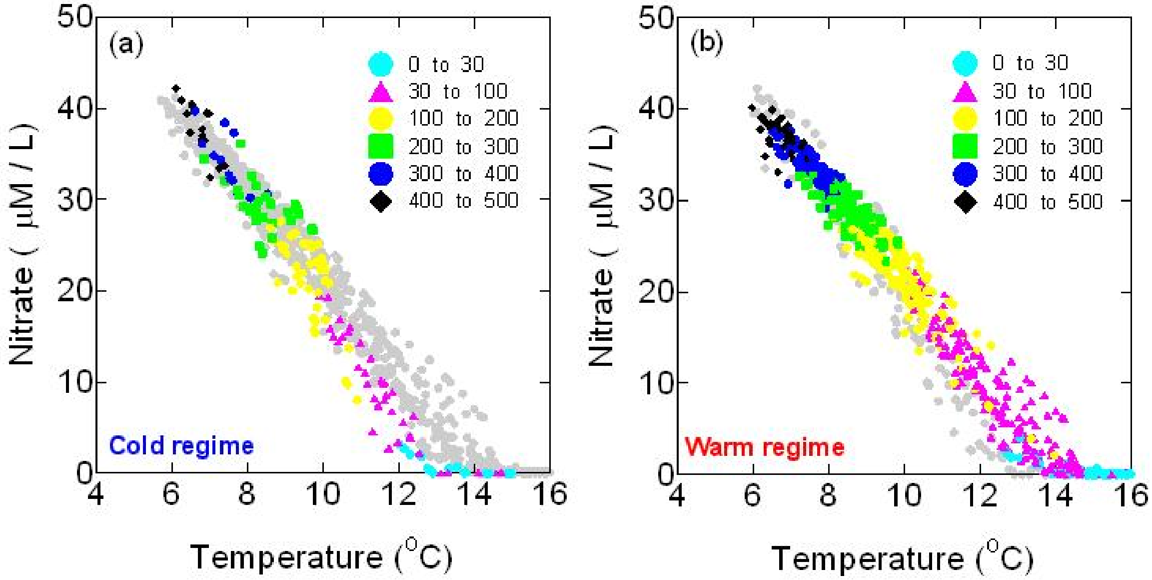


Fig. 2.5. Nitrate-temperature scatter plots in the cool regime (a) and in the warm regime (b). Colors represent sampling depth ranges and gray background dots are plotted to compare with the other regime. The slope of nitrate versus temperature changed after the climate regime shift by the surface intensified warming for the mid-depth waters (30 m – 200 m).

References

Akima, H., 1970. A new method of interpolation and smooth curve fitting based on local procedures. Journal of the ACM, vol. 17(4), pp. 589-602.

Bograd, S.J. and R.J. Lynn, 2003. Long-term variability in the Southern California Current System. Deep-Sea Research part II, vol. 50, pp.2355-2370.

Davis, E.D., 1985. Drifter observations of coastal surface currents during CODE: The method and descriptive view. Journal of Geophysical Research, vol. 90(C3), pp. 4741-4755.

Di Lorenzo, E., A.J. Miller, N.Schneider and J.C. McWilliams, 2005. The warming of the California Current: Dynamics, thermodynamics and ecosystem implications. Journal of Physical Oceanography, vol 35, pp.336-362.

Gill, A.E., 1982. Atmosphere-ocean dynamics. New York, Academic Press.

Hayward, T. L., R.R.Baumgartner, D.M. Checkley, R.Durazo, G. Gaxiola-Castro, K.D. Hyrenbach, A.W. Manytla, M.M. Mullin, T. Murphree, F.B. Schwing, P.E. Smith and M.J. Tegner, 1999. The state of the California Current in 1998-1999: Transition to cool-water conditions. California Cooperative Oceanic Fisheries Investigations Reports vol. 40, pp. 29-62.

Hayward T.L. and E.L. Venrick, 1998. Nearsurface pattern in the California Current: coupling between physical and biological structure. Deep-Sea Research Part II, vol. 45 (8-9), pp. 1617-1638.

Hickey, B.M., 1998. Coastal oceanography of western North America from the tip of Baja to Vancouver Island in The Sea, The global coastal ocean; Regional studies and synthesis, vol.11, edited by A.R. Robinson and K.H. Brink, Wiley, New York, pp.345-393.

Hsieh, C.H., S.M. Glaser, A.J. Lucas and G. Sugihara, 2005. Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. Nature, vol 435 (7040), pp. 336-340.

Huyer, A., 1983. Coastal upwelling in the California Current System. Progress in Oceanography, vol. 12(3), pp. 259-284.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace and R.C. Francis, 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteo. Soc., vol 78, pp.1069-1079.

McGowan, J.A., S.J. Bograd, R.J. Lynn and A.J. Miller, 2003. The biological response to the 1977 regime shift in the California Current. Deep-Sea Research, vol. 50, pp.2567-2582.

Miller, A.J., D.R. Cayan, T.P. Barnett, N.E. Graham and J.M. Oberhuber, 1994. The 1976-77 climate shift of the Pacific Ocean. Oceanography, 7, 21-26.

Palacios, D.M., S.J. Bograd, R. Mendelsshon, and F.B. Schwing, 2004. Long-term and seasonal trends in stratification in the California Current, 1950-1993. Journal of Geophysical Research, vol. 109(C10), doi:10.1029/2004JC002380.

Peterson, W. T., and F. B. Schwing, 2003. A new climate regime in northeast pacific ecosystems. Geophysical Research Letters, Vol. 30, No. 17, 1896, doi:10.1029/2003GL017528.

Roemmich, D. and J. A. McGowan, 1995. Climatic warming and the decline of zooplankton in the California Current. Science, vol. 267, pp. 1324-1326.

Strub, P.E., P.M. Kosro, and A. Huyer, 1991. The nature of the cold filaments in the California Current System. Journal of Geophysical Research, vol. 96(C8), pp.14,743-14,768.

Venrick, E., 1998. The phytoplankton of the Santa Barbara basin: patterns of chlorophyll and species structure and their relationships with those of surrounding stations. CalCOFI reports, vol. 39, pp. 124 – 132.

Chapter 3 Climate and Coastal Algal Blooms in the Southern California Bight

ABSTRACT

Surface chlorophyll measured at the Scripps Pier in the Southern California Bight (SCB) for eighteen years (1983 – 2000) reveals that the spring bloom occurs with irregular timing and intensity each year, unlike sea-surface temperature (SST), which is dominated by a regular seasonal cycle. In the 1990's, the spring bloom occurred earlier in the year and with larger amplitudes compared to those of the 1980's. Seasonal anomalies of the chlorophyll have no significant correlation with local winds, offshore winds, or upwelling index anomalies. Consequently, classical coastal upwelling may not be the process that drives chlorophyll variations in the nearshore SCB.

The annual mean Pier chlorophyll concentration exhibits a clear increasing trend with no concomitant trend evident in the Pier SST over these two decades. The interannual variations of the Pier SST and chlorophyll is not correlated with tropical El Niño or La Niña conditions over the entire observing period, but a few strong El Niño and La Niña events have significant impacts on the Pier data. The Pier chlorophyll is highly coherent at 3 – 7 year periods with nearby offshore *in situ* surface chlorophyll observations at the CalCOFI (California Cooperative Fisheries Investigations) station 93.27. Both the Pier and CalCOFI station 93.27 (12.5 km offshore) are on the continental shelf (water depth<200), but the Pier chlorophyll observations have magnitudes that are roughly one to two orders greater than the offshore surface chlorophyll observed by CalCOFI.

3.1 Introduction

The episodic occurrences of discolored water, nearshore, are commonly called Red Tides or Harmful Algal Blooms (HABs). They have been reported in the Southern California Bight for over 100 years [*Torrey*, 1902]. They are due to relatively sudden population explosions of phytoplankton. Beginning around 1918, W.E. Allen began a 20-year program of monitoring phytoplankton populations here by daily counts of cell numbers from water samples taken at the end of Scripps Pier (32^o 52.0'N, 117^o 15.4'W, Fig. 3.1) [*Allen*, 1938; *Allen*, 1941]. In his summary paper he discussed the frequency of what he called "red waters" (six in 30 years) but without really defining that term. He emphasized inter-annual variations of the unusually large blooms he measured and attempted to determine their longshore and offshore extent. He could find no convincing relationship to local temperature changes.

Climate changes impact on the biosphere. They might alter the seasonal cycles of biological phenomena such as the blooming timing of plants [*Cayan et al.*, 2001; *Penuelas and Filella*, 2001] and the migration of butterfly and birds [*Penuelas and Filella*, 2001]. These phenological changes also occur in marine ecosystems. *Reid et al.* [1998], for example, showed phytoplankton trends in the North Atlantic due to global warming and *Tont* [1987], in a reanalysis of part of Allen's data, found that several species of diatoms "respond" to climatic fluctuations.

Substantial climate changes have occurred in the California Current System (CCS) in recent several decades, *e.g.,* surface intensified warming and strengthened stratification [*Roemmich and McGowan*, 1995; *Bograd and Lynn*, 2003; *Kim and Miller*, 2007], sea level rise [*Roemmich*, 1992], and circulation pattern changes [*Bograd and

Lynn, 2003; *Lentz and Chapman*, 2004]. These oceanic climate changes might interact with changes in the available light and nutrient supply to affect photosynthesis in the euphotic zone and eventually alter primary production. This study asks the question: Can we detect such biological changes in the nearshore?

Physical climate changes are evident in relatively intensive observations, but climate-driven primary production changes over decadal time scales are not well understood because of lack of data. Ship-measured time series, for example California Cooperative Fisheries Investigation (CalCOFI) data, have low temporal resolution as compared to the time scale of doubling times of phytoplankton populations. Satellites are the only feasible way to give large-scale coverage with high temporal frequency. But satellite chlorophyll data adjacent to the coastline, where most primary production of the world ocean occurs, are well known to exhibit some biases because of the effects of colored dissolved organic matter, light-scattering inorganic particulates, and land surface reflection [*Kahru and Mitchell*, 1999; *Legaard and Thomas*, 2006].

Thus it is still an open question how primary production responds to the recent decadal climate changes. Due to the limitation of coastal data, characteristics of very nearshore chlorophyll variation and the relationship between nearshore chlorophyll measurements and broader-scale patterns observed offshore have remained unclear. This issue can offer an understanding of physical-biological characteristics and long-term marine ecosystem changes in the Southern California Bight (SCB). In this study, we will analyze seasonal, interannual, and long-term variability of sea surface temperature (SST) and surface chlorophyll, presumably primary production, using a unique long-term (18-year) Scripps Pier time series combined with the CalCOFI dataset (Fig. 3.1).

One of the prominent ecosystem features in the CCS is the spring phytoplankton bloom along a narrow coastal band (within 50 km from the coastline), resulting in strong seasonality and an inshore-offshore gradient of primary production [*Strub et al.*, 1990; *Thomas et al.*, 1994; *Legaard and Thomas*, 2006]. The spring bloom generally occurs within 20 km of the coastline in the CCS [*Henson and Thomas*, 2007]. Both amplitude and standard deviation are one or two orders of magnitude greater than offshore (Fig. 3.2). Does the highly variable chlorophyll at the coastal band respond to dramatic upper ocean climate changes during recent decades? Has spring bloom timing and consequent seasonal cycle changed? We address this issue of seasonality and the spring bloom by characterizing spring bloom timing and intensity using our two decades of twice-a-week samples at Scripps Pier.

The narrow coastal band is the area where most primary production occurs, and coastal upwelling is considered to be the driving mechanism that brings nutrients upward in the CCS; however, the Southern California Bight (SCB) has low seasonality compared to other CCS regions, and the influence of upwelling favorable winds and wind stress curl on the seasonal patterns of chlorophyll concentration is confined only to the north of the SCB [*Strub et al.*, 1990]. In the SCB, therefore, the coastal upwelling might not be a dominant driving mechanism of nutrient supply for the high chlorophyll concentration of the coastal band.

Interannual variability of coastal (0-25 km) chlorophyll concentration has weakly significantly correlation (< 0.3) with anomalous upwelling favorable winds [*Strub et al.*, 1990]. Moreover, this small but significant correlation is confined only to the north of 35 ^{o}N in the CCS while in the SCB upwelling favorable winds explain less than 5% of the interannual chlorophyll variations [*Strub et al.*, 1990]. Therefore in the SCB both seasonal and interannual variations of chlorophyll have insignificant correlation with upwelling favorable winds. *Chelton et al.* [1982] also found that wind induced coastal upwelling has insignificant relation with variations in zooplankton biomass. So can classical coastal upwelling explain the nearshore high primary production? What other possible physical mechanisms can bring nutrients to the high chlorophyll nearshore coastal band? We address this issue by calculating the correlations between the chlorophyll time series at Scripps Pier with NOAA upwelling index, Niño 3.4 index, and several physical factors observed locally at the Scripps Pier such as wind stress, air temperature, and cloud cover.

Leggard and Thomas [2006] used daily SeaWiFS data to show that interannual variations in SST and chlorophyll are generally governed by El Niño and La Niña conditions in the CCS. The physical and biological impacts of El Niño/Southern Oscillation (ENSO) events in the SCB have been well documented [*Chelton and Davis*, 1982; *Strub et al.*, 1990; *Karl et al.*, 1995; *Chavez et al.*, 1999; *Bograd and Lynn*, 2001]. Notice however that previous studies focus on individual El Niño/La Niña events or a restricted time period. As *Leggard and Thomas* [2006] pointed out, ENSO impacts in the SCB over interannual time scales with relatively short record length may be biased. We address this issue with a longer-term view by comparing the two-decade Scripps Pier time series with Niño 3.4 index to assess the overall ENSO response in the SCB as well as the effects of individual El Niño/La Niña events.

Roemmich and McGowan [1995] show surface intensified warming and a 70% decrease of macrozooplankton biomass over recent decades using the CalCOFI data.

They suggested that the surface warming might suppress the upwelling cell and reduce nutrient supply, which might result in reduced primary production and consequent macrozooplankton decline. Identifying a long-term trend in chlorophyll is fundamental to making a possible link between climatic warming and the zooplankton decrease. We address this issue by analyzing the long-term trends in the Scripps Pier time series.

Previous studies show trends of surface chlorophyll [*Gregg and Conkright*, 2002; *McClain et al.*, 2004; *Hirawake et al.*, 2005], depth-integrated chlorophyll [*Behrenfeld et al.*, 2006], and net primary production [*Behrenfeld et al.*, 2006]. However, these studies have different approaches and some of them have inconsistent results. In addition, they focus on global changes rather then local changes except for *Hiwarake et al.* [2005]. Although *Gregg et al.* [2005] show that California/Mexico shelf has an increasing chlorophyll trend, the data they use for the analysis are only for a limited time span (1998-2003) and they are derived from 9-km resolution SeaWiFS images so it is hard to resolve very nearshore chlorophyll changes.

Here, we examine the temporal variability of phytoplankton, nearshore, from samples taken at Scripps Pier and analyzed for chlorophyll content. We compare the observed variations to that of climate. Has seasonal cycle of the Pier chlorophyll changed? Is the Pier chlorophyll variability correlated with physical factors such as winds, cloud cover, and Equatorial El Niño/La Niña signal? Does the Pier chlorophyll have a significant long-term trend?

3.2 Data

Three independent data sets of surface chlorophyll were used to analyze spatial and temporal variability: the Scripps Pier time series (SST and surface chlorophyll), CalCOFI ship-based measurement, and SeaWiFS satellite-derived data (Fig. 3.1). We focused on the Scripps Pier time series to understand seasonal, annual, and long-term variations of surface chlorophyll, and to examine the spatial connection between the Scripps Pier and nearby CalCOFI stations. SST, Niño3.4 SST index, NOAA upwelling index, and other physical variables such as wind, cloudiness, and sea surface salinity were introduced to attempt to explain the Scripps Pier chlorophyll variation. Niño 3.4 index is area averaged monthly SST anomaly in the eastern tropical region 5°S-5°N, 170°W-120°W [*Trenberth*, 1997]. It is smoothed by taking 5 month running mean.

3.2.1 Scripps Pier time series

Surface chlorophyll, sea surface temperature (SST), sea surface salinity (SSS), cloud cover, and wind magnitude were measured at the Scripps pier (Fig. 3.1) from Feb 17, 1983 to Oct 1, 2000. Sampling frequency for chlorophyll was twice a week, and most of time two samples were taken in the morning with a 30-minute interval on same day. Samples were filtered, extracted, and read by fluorometer (Venrick and Hayward 1984). We therefore analyzed chlorophyll time series with 1847 measurements after averaging the same-day samplings. This Scripps Pier time series is a rare long-term record of chlorophyll with high temporal sampling frequency that enables us to analyze long-term trends as well as short-term seasonal and annual changes. Notice that SST and SSS have been measured *daily* at the Scripps Pier since 1916.

The Scripps Pier chlorophyll has both a linear long-term trend and nonlinear pulse-like signals of high frequency, large amplitude algal blooms (Fig. 3.3). There are 5 pulses with unusually large magnitudes between 18.19 and 218.95 (mg/m^3) in May 1985, Jun 1991, Jan through Mar 1995, Apr 1996, Feb 1997, and May 1998. Raw data average including these 5 pulse events is 2.49 mg/m^3 and standard deviation is 7.70 mg/m^3. Without these pulses, average and standard deviation of surface chlorophyll are 1.89 mg/m^3 and 1.90 mg/m^3, respectively.

3.2.2 CalCOFI

The CalCOFI program started hydrographic surveys and macrozooplnakton biomass measurements in 1949 to investigate the collapse of sardine population in the CCS. Biological and chemical properties have been measured since 1984 including chlorophyll and major nutrients with the current CalCOFI grid of 66 nominal stations (Fig. 3.1). Spatial resolution is roughly 70 km, but inshore stations in the station map are around 10 – 15 km apart in the cross-shelf direction.

3.2.3 SeaWiFS

Satellite data are of great benefit to our understanding of large-scale spatial patterns. Both CZCS (Coastal Zone Color Scanner, 1978-1986) and SeaWiFS (1997-present) images show a narrow coastal band with high chlorophyll values and oligotrophic offshore water as a general pattern of mean surface chlorophyll in the CCS [*Strub et al.*, 1990; *Legaard and Thomas*, 2006]. However, coastal ocean is optically complex because of suspended inorganic particles, dissolved organic matters, and a bottom reflectance, so coastal chlorophyll data derived from satellites have systematic and random errors [*Kahru and Mitchell*, 1999; *Darecki and Stramski*, 2004; *Legaard and Thomas*, 2006]. In this study, we only present a brief analysis of the SeaWiFS data in comparison to the in situ chlorophyll data.

Remotely sensed surface chlorophyll, derived from SeaWiFS Level 3 data with 8-day temporal resolution and 9 km spatial resolution, was compared with CalCOFI chlorophyll (Fig. 3.4a) and Scripps Pier chlorophyll (Fig. 3.4b). Notice that discrepancy between magnitudes of Pier chlorophyll and SeaWiFS data is larger than those of CalCOFI and SeaWiFS chlorophyll data. This is partly because SeaWiFS data with 9 km resolution are obtained by smoothing 1 km resolution data so they are not able to resolve high variability of the coastal ocean. The offshore station has a higher R-square value than the Pier station (Fig. 3.4c, 3.4d), which exhibits a strong bias.

The discrepancy between the shipboard measurement and the satellite observation was explored and found to depend on season and location of each station (Fig. 3.5). Continental shelf water (< 200 m water depth, Fig. 3.1c) has much higher chlorophyll concentration than SeaWiFS derived chlorophyll. On the contrary, SeaWiFS chlorophyll is well matched with CalCOFI measurements at offshore stations 300 km away from the coastline that have water depths deeper than 3000 m. CalCOFI chlorophyll is higher than SeaWiFS in Winter (JFM) and vice versa in Fall (OND) at CalCOFI stations between the coastal band and open ocean, whose water depths are between 500 m and 1000 m. A better algorithm for the SeaWiFS chlorophyll is needed for the area adjacent to the coastline, which is the focus area of our study [*Kahru and Mitchell*, 1999]. So we drop further use of the SeaWiFS data in this study and instead concentrate solely on the in situ chlorophyll data.

3.3 Results

3.3.1 Seasonality and the Spring Bloom

Primary production in the coastal band of the CCS has often been thought to be sustained by coastal upwelling, which occurs in spring and is indicated by cold SST and high SSS, *i.e.* more dense water, and alongshore upwelling-favorable winds. The coastal areas off Oregon, Northern and Central California have strong upwelling favorable winds especially in springtime and consequent strong coastal upwelling and prominent phytoplankton blooms. *Barth et al.* [2007], for example, show how the coastal ocean ecosystem in the northern California Current is sensitive to the upwelling favorable wind stress. However, the Southern California Bight has relatively weak upwelling favorable winds and more complicated topography than the other areas of the U.S. West Coast [*Winant and Dorman*, 1997]. Moreover, most peaks of Pier chlorophyll occurred at different timing of each year (Fig. 3.6). Linear relationship with SST or SSS cannot explain the chlorophyll variability. It is still an open question whether the SCB ecosystem is also regulated by the classical coastal upwelling.

Monthly chlorophyll climatology was calculated for the Scripps Pier and every CalCOFI station (not shown) over 18 years (1983-2000). The CalCOFI data showed that chlorophyll has spring maxima at coastal stations and winter maxima at offshore stations, which is consistent with the analysis of *Hayward and Venrick* [1998]. Coastal stations can be separated into two groups, Northern and Southern coast regions, where the Southern coast has less seasonality than the Northern [*Hayward and Venrick*, 1998].

Scripps Pier is located at the coastline and roughly 330 m long. It is geographically close to the Southern coast region [*Hayward and Venrick*, 1998], and 12 km away from the nearest CalCOFI station 93.27. However, the chlorophyll at the Pier is dramatically more variable than CalCOFI stations, and the Pier chlorophyll is not well represented by a monthly climatology (Fig. 3.6c). The monthly climatology of the Pier data show that chlorophyll has a spring maximum in April and a fall minima in October, but in any given year the timing of the spring maximum does not necessarily coincide with the climatological peak (Fig. 3.6c).

The monthly mean chlorophyll time series has a minimum of 0.14 mg/m^3 and a maximum of 9.85 mg/m^3 without the pulse events (39.23 mg/m^3 with the pulse events), while monthly SST varies with a range between 13 – 23 ^{o}C (Fig. 3.6). Notice that the mean normalized standard deviation of chlorophyll (0.61 w/o pulses, 1.34 w/ pulses) is approximately several times greater than that of SST (0.15). SST is predominantly governed by a seasonal cycle, and always exhibits summer maxima and winter minima (Fig. 3.7a). But chlorophyll, in contrast, is not dominated by a clear seasonal cycle and it shows more complicated features (Fig. 3.7b). The chlorophyll concentration is higher in

1990's than those in 1980's. Thus it has an increasing linear trend except for summer (Fig. 3.7b,c).

The Pier chlorophyll has a positively skewed distribution (Fig. 3.8). The temporal sampling frequency of the Scripps Pier time series, twice a week, is high enough to resolve phytoplankton blooms. Defining a spring bloom can be arbitrary. In this study, two different thresholds were applied to define a phytoplankton bloom since the five pulse events have one or two order higher magnitudes greater than mean and median of the data. One is a *Major Bloom* threshold (17.88 mg/m^3), which is 2 standard deviations of the raw data including the five pulses. The other is a *Minor Bloom* threshold (5.70 mg/m^3), 2 standard deviations of the raw data without major blooms. Only 1.3 % of total samples (24 out of 1847) have higher chlorophyll concentrations than the major bloom threshold.

The number of blooms each month and for each year is counted and their concentrations are averaged (Fig. 3.9). Both major (Fig. 3.9ab) and minor (Fig. 3.9cd) blooms tend to occur earlier and more frequently in the 1990's than in the 1980's. Averaged chlorophyll concentration of the blooms (Fig. 3.9bd) increased in recent years. Minor blooms show more detailed phenological changes. 92 % of minor blooms from 1983 to 1994 occurred in Spring/Summer (Apr-Sep). But 41 minor blooms out of 53 occurred in winter/spring (Feb-May) after 1994. Some years in the 1980's (1983, 1984, 1987, and 1989) showed no major/minor blooms for the entire year and phytoplankton blooms did not occur in February or March until 1995.

Physical signature such as cold SST and upwelling favorable winds should necessarily appear if coastal upwelling controls chlorophyll concentration at the Pier.

Correlation coefficients were calculated to examine the linear relationship of physical variables with the Pier chlorophyll (Table 3.1). Major blooms are not included for this linear statistics. Local winds measured at the Pier and offshore winds measured at station 46025 (Fig. 3.1) of National Data Buoy Center (NDBC) are used to calculate correlation as well as the Pier SST, SSS, surface density, and cloud cover, and physical indices (Niño 3.4 and NOAA upwelling index).

Correlation coefficients are significant for some of variable pairs, for example, density and temperature (0.36), pier wind magnitude (local wind) and NDBC wind magnitude (offshore wind, 0.48), and Pier wind power and NDBC wind power (0.58), where wind power is proportional to the cube of wind magnitude. Yet no variable shows a highly significant relationship with chlorophyll (Table 3.1). This implies that chlorophyll variation is highly nonlinear and/or forced by other processes [*Sugihara and May*, 1990].

The Pier SST has significant correlation with local (-0.27) and offshore (-0.59) winds. However it has no significant correlation with the Pier chlorophyll (-0.14). It means that although coastal upwelling may affect chlorophyll concentration, the correlation coefficient is so small that SST can explain only 2 % of the chlorophyll variations. This implies that the biological response to regular physical variation of SST is not linear and occurs in a much more complicated way.

3.3.2 Interannual variation and El Niño/La Niña events

Tropical El Niño conditions are one of the important factors to affect interannual variations in the SCB. El Niño signal of sea level changes in the CCS propagates from the equator to the North along the coast [*Chelton and Davis*, 1982; *Strub and James*, 2002]. *Strub and James* [2002] showed that sea surface heights and geostrophic transports in the Northeast Pacific were influenced by the 1997-1998 El Niño. Not only physical conditions were affected by El Niño events, but also biological changes of chlorophyll and zooplankton were observed in the CalCOFI data [*Legaard and Thomas*, 2006]. *Reid et al.* [1985] found that oceanic warm-water species appeared at the Scripps Pier during the 1982-84 El Niño event. In this section, interannual variations of physical biological interaction will be examined over several El Niño-Southern Oscillation (ENSO) events, using the Niño3.4 index and the 18-year Scripps Pier data of SST and chlorophyll.

Fig. 3.10 shows time series of Niño 3.4 anomalies and smoothed seasonal anomalies of Pier SST and chlorophyll. Niño 3.4 index has insignificant correlation with the Pier SST (correlation coefficient 0.46) or chlorophyll (correlation coefficient –0.13 without major blooms) over the entire time series including several ENSO events. This implies that remote forcing from the equator does not consistently affect physical and biological variability in the SCB [*McGowan et al.*, 1998].

Notice, however, that both physical (SST) and biological (chlorophyll) factors at the Pier are directly linked to the ENSO signals after the development of 1997/98 El Niño (Fig. 3.10) even though the Niño 3.4 index is area averaged SST and the Pier times series is a point measurement. During the 1997/98 El Niño, chlorophyll anomalies were substantially low, and they started to increase during the 1998/1999 La Niña (Fig. 3.3, 3.6, and 3.10). Correlation coefficients with the Niño 3.4 anomalies are 0.83 for the SST and –0.76 for the chlorophyll without major blooms since the onset of the 1997/1998 El

Niño (Aug 1997 – Oct 2000). Details of physical and biological responses to the 1997/98 El Niño and the 1999 La Niña in the CCS are well documented by previous studies [*Bograd and Lynn*, 2001; *Legaard and Thomas*, 2006].

Not until after the onset of 1997/98 El Niño, Pier chlorophyll is significantly negative correlated with Niño 3.4. How long does the Pier chlorophyll respond to the ENSO signal after the 1997/98 El Niño? Is the Pier chlorophyll correlated with the equatorial warming signal even after the 1998/99 La Niña? Does the Pier chlorophyll recover back to the normal status? Since the Pier chlorophyll was interrupted in 2000, we are not able to answer these questions with the Pier time series. However, monthly mean sea level at La Jolla (1924 – present) shows that the ENSO influence on sea level in the SCB disappeared after the 1998/99 La Niña event. *McGowan et al.* [1998] also showed that warm and cold La Jolla SST anomalies due to the equatorial El Niño and La Niña events are persistent no longer than 2 years between 1916 and 1993.

Scatter plots of Niño 3.4 index versus the Pier data, SST and chlorophyll, show the equatorial ENSO impact on the Pier SST and chlorophyll for each El Niño/La Niña event (Fig. 3.11). There were six El Niño and four La Niña events during the Pier observation period, 1983-2000, according to the El Niño definition of *Trenberth* [1997]. The El Niño event of 1982/83 was excluded for data analysis because of short record length.

High temperature and low chlorophyll are well-known characteristics of El Niños, and vice versa for La Niñas. However, not all of ENSO episodes show the consistent temperature and chlorophyll changes (Table 3.2). Some of the larger ENSO events appear to exhibit a linear relationship with the Pier SST and/or chlorophyll during their evolution, but overall there is no consistent relationship (Table 3.2). When Niño 3.4 is smaller than this threshold ENSO definition, remote forcing from the equator does not consistently contribute to driving physical and biological variability in the nearshore SCB.

3.3.3 Long-term trend of the Pier surface chlorophyll

The time series of the Pier chlorophyll monthly mean anomalies shows an increasing trend (Fig. 3.3). The trend is especially apparent in both the time series of annual mean anomalies and annual median anomalies (Fig. 3.12). The trend of the Pier chlorophyll was calculated by linear regression (Table 3.3). Both monthly averaged chlorophyll (Var1, Var3) and monthly averaged chlorophyll anomalies (Var2, and Var4) have significant trends (p-value<0.05) whether major blooms are included or not. The Pier SST does not have a significant linear trend during the observation period, 1983-2000. But notice that longer-term daily SST time series since 1916 shows more frequent warming episodes after 1977 and consequently warming trend [*McGowan et al.*, 1998].

The slope of the Pier surface chlorophyll linear trend (Var4) is 0.1064 mg/m^3/year (Table 3.3). *Gregg et al.* [2005] analyzed linear trends of global SeaWiFS data for 6 years from 1998 and 2003 after removing climatological seasonal cycle. They showed a significant increasing trend for the 6 years in the Northeastern Pacific coast (California/Mexican shelf) with a slope, 0.287 mg/m^3/year. This slope is larger than that of the Pier chlorophyll trend probably because their trend for the 6 years might be more affected by interannual variability than the long-term Pier chlorophyll trend. Different observation time periods of the SeaWiFS and Pier data set could also result in different slopes. In addition, SeaWiFS data might contain significant errors at the nearshore close to the coastline where the productivity is the highest (Fig. 3.5).

Behrenfeld et al. [2006] showed two significant linear trends of global ocean net primary production (NPP) using satellite derived chlorophyll data. One is a positive trend from 1997 to 1999 due to the transition from 1997/98 El Niño to 1998/99 La Niña and the other is a negative trend from 1999 to 2006 due to the upper ocean warming [*Behrenfeld et al.*, 2006]. In the SCB, NPP decreased roughly 0 – 20 % from 1999 to 2004 [*Behrenfeld et al.*, 2006]. Unfortunately the Pier time series have a gap between 2000 and 2005, so we cannot compare directly with the trend of SeaWiFS data. However, notice that the Pier chlorophyll also increased from 1998 to 1999 because of the El Niño/La Niña transition and decreased from 1999 to 2000 (Fig. 3.12). The Pier time series from 2005 to present have a consistent increasing trend with the long-term trend since 1983 [*Carter et al.*, 2007].

What mechanism can explain this chlorophyll trend at the Pier? The fundamental controlling factors of primary production are light and nutrients, but nutrient supply is the more important limiting factor at the latitude of the SCB (30 – 34 ^{o}N).

Coastal upwelling is a well-known mechanism that brings nutrient rich cold water to the euphotic zone in the CCS. Nutrients carried by fresh water runoff from rainfall can be a source of the nutrient supply too. However, local and offshore winds have no significant correlation with the Pier chlorophyll (section 3.1).

Another possible source of nutrients is offshore water. Since the Pier is on the continental shelf, there is cross-shelf exchange by physical forcing like meandering jets, eddies, filaments, tides, or internal waves. Fig. 3.13 shows high coherency at low frequency band (3-7 years), which implies that there is certain physical process to connect nearshore and 11.5 km offshore even though the Pier is located very close to the coastline. Not only cross-shelf coherency of the surface chlorophyll but also alongshore coherency of coastal chlorophyll is evident (J. McGowan, unpublished data). McGowat et al. (1998) show significant coherency of SST at low frequencies (< 20 cycle/year) between Port San Luis and 8 coastal stations in the SCB.

3.4 Summary and Discussion

The SST and chlorophyll time series observed at the Pier in the SCB from 1983 though 2000 show that surface chlorophyll exhibits much higher variability than SST. The monthly SST has a pronounced seasonal cycle (Fig. 3.7a) that shows maximum SST always occurring in summer (July – Sep) and minimum in winter (Dec – Feb). In contrast, the monthly chlorophyll exhibits a maximum that appears each year in a far more variable time frame, between February and August (Fig. 3.7b). For the twice-weekly time series, spring blooms occurred in May or later in the 1980’s but they often appeared as early as February in the 1990’s. More importantly, spring blooms were very infrequent and weak during the 1980’s but occurred with much greater frequency and intensity during the 1990’s (Fig. 3.9). The annual mean Pier chlorophyll consequently exhibits an increasing trend over these two decades (Fig. 3.12).

The earlier phytoplankton blooming might be caused by the upper ocean warming and increased buoyancy. Light exposure time of phytoplankton can be longer because of the increased buoyancy leading to higher primary production before spring. This might be related to the zooplankton blooming time change observed by *McGowan et al.* [2003]. They reported that blooming month of zooplankton biomass shifted from July to May. McGowan et al. (2003) does not show phytoplankton blooming, but in general phytoplankton blooming is followed by zooplankton blooming with a few weeks time lag [*Townsend*, 1984; *Haldorson et al.*, 1993].

Interannual variation of the Pier chlorophyll is not significantly correlated with the SST, cloud cover, local or offshore winds, upwelling index, or Niño 3.4 index (Table 3.1). Some of El Niño (La Niña) events show high (low) SST anomalies and low (high) chlorophyll (Table 3.2). But these characteristics did not appear at the Pier for all of tropical ENSO events [*McGowan et al.*, 1998]. Power spectra show that the Pier chlorophyll has a peak at annual time scale but nearby CalCOFI stations 93.27 and 93.28 do not (Figure is not shown). This is consistent with a decorrelation length scale of chlorophyll. Seasonality at the southern coast of the SCB is not stationary, so the quarterly sampling of CalCOFI measurement might not be able to resolve it. The weak seasonality around this area has been documented by Hayward and Venrick (1999). However, at low frequency (3 – 7 years), both the Pier and CalCOFI stations 93.27 and 93.28 have peaks in power spectra. Moreover they have high coherency in the low frequency band (Fig. 3.13), although stations further from the coastline have smaller magnitudes of chlorophyll (Fig. 3.3). The low frequency coherency vanishes for stations further offshore from CalCOFI station of 93.30, which is 26 km away from the Pier.

Surprisingly, both seasonal and interannual variation of the Pier chlorophyll is not significantly correlated with local winds, offshore winds, or upwelling index (Table 3.1). This suggests that classical coastal upwelling is not an important process contributing to the Pier chlorophyll variation at the southern coast of the SCB, perhaps because the area is more sheltered, with relatively weaker and less persistent winds, and has more complicated bottom topography than the California Current region off central and northern California.

The Pier surface chlorophyll increased from 1983 to 2000 (Table 3.3). What is the role of the increasing trend of the Pier chlorophyll in the food web of marine ecosystem? Ware and Thomson (2005) found strong trophic linkages of alongshore variations of chlorophyll, zooplankton, and resident fish in British Columbia as well as a linear relationship between mean chlorophyll concentration and resident fish yield for 11 locations along the continental margin of Northeastern Pacific. This suggests that fish yield is controlled by bottom-up forcing of primary production.

If the positive correlation between chlorophyll and zooplankton can be also applied to the CalCOFI dataset (although it is not clear whether this correlation can be applied to temporal variations), the increasing trend of the Pier chlorophyll contradicts the large decrease of macrozooplankton observed over this time period (http://www.calcofi.org/newhome/data/zooplankton.htm). Notice that the increasing trend of the Pier chlorophyll is not only confined to the Pier station, but also it has significant coherency with CalCOFI chlorophyll. Moreover, depth-integrated chlorophyll for the whole CalCOFI grid shows a positive trend as well (E. Venrick, personal communication, 2007). The amount of long-term chlorophyll increase might not be big enough to give positive forcing to zooplankton and to have consistent linear relationship that *Ware and Thomson* [2005] found.

One of possible mechanisms to explain the increasing chlorophyll and decreasing zooplankton trends would be decreasing grazing pressure of zooplankton on phytoplankton. One other possibility is different size classification of phytoplankton. Surface warming could result in less nutrient supply presumably less new production of big phytoplankton like diatoms. However, small phytoplanktons are more productive with less nutrient environment [*Moloney and Field*, 1989]. Low nutrient conditions are beneficial to small phytoplankton rather than large phytoplankton and it has less efficient trophic transfer to upper trophic levels.

There are many remaining questions regarding the source of nutrients at the Pier to require further analysis: 1) What is the physical mechanism to bring nutrients to the Pier to result in the long-term increasing trend? 2) What physical processes cause persistent high surface chlorophyll with one order higher magnitude than offshore? 3) Is fresh water input from rainfall related to phytoplankton blooms at the Pier? 4) How is species composition changed? To answer these questions long-term measurements with sampling frequency higher than time scale of chlorophyll variations would be necessary [*Pennington and Chavez*, 2000]. Vertical profiles of both chlorophyll and nutrients would be helpful. Satellite algorithm development is also needed to improve the very nearshore data. Numerical modeling studies are needed to better understand the physical mechanisms behind this ecosystem variability.

3.5 Acknowledgments

This work forms a part of the Ph.D. dissertation of HJK. We gratefully thank all the technicians and scientists for the Scripps Pier time series and CalCOFI cruises. The Pier time series measurement was conducted by Patricia Walker and Connie Fey and was supported in part by a grant from the MacArthur foundation to JM and by CalCOFI. AJM gratefully acknowledges funding from NSF through the California Current Ecosystem LTER (OCE-0417616), NASA (NNG06GC98G), DOE (DE-FG02-04ER63857), ONR (N00014-05-1-0363) and NOAA through the ECPC (NA17RJ1231). The views expressed herein are those of the authors and do not necessarily reflect the views of these agencies.

Table 3.1. Correlation coefficients between pier chlorophyll and other variables were calculated using monthly (coef 1) and seasonal anomalies (coef 2). If the p-value is less than 0.05, the number is printed in bold. Wind stress at NDBC station 46025 (33.75 N 119.08 W) was used to calculate variables; NDBC spd, NDBC τ, and NDBC power represent wind speed ($|\hat{U}|$, m/s), alongshore pseudo stress ($V|V|$, N/m^2), and cubic wind speed (vertical mixing)($|\hat{U}|^3$, m^3/s^3) respectively, where the NDBC wind vector $\hat{U} = (U, V)$. The alongshore wind stress is upwelling favorable if it has a negative sign.

	SST	**SSS**	**Density**	**Cloud**	**Pier spd**	**Pier Power**	**NDBC spd**	**NDBC τ**	**NDBC power**	**Niño3.4**	**Upwelling index**
Coef 1	**-.14**	-.04	.13	.04	.09	.07	.08	**-.019**	.05	-.09	**.16**
Pvalue	**.0415**	.5687	.0664	.5985	.2136	.2912	.2674	**.0060**	.5112	.2013	**.0196**
Coef 2	**-.14**	-.03	.10	-.04	-.03	-.02	-.03	-.02	-.04	-.13	-.02
Pvalue	**.0430**	.7155	.1364	.5384	.6450	.8073	.6606	.7392	.5304	.0653	.7367

Table 3.2. Linear regression coefficients and R^2 values for each El Niño/La Niña event between Niño 3.4 anomalies and the Scripps Pier time series anomalies. A five-month moving average was applied to Niño 3.4 and the Scripps Pier time series. Numbers are printed in bold if average is larger than standard deviation so average±std keeps one sign and if p-value is less than 0.05. Major bloom events are not included for this linear statistics.

(a) El Niño events

	SST (°C)				Chl-a (mg/m³)			
	Average ±std	Slope	R^2	p-value	Average ±std	Slope	R^2	p-value
Jul 86 – Feb 88	-0.3±0.44	0.17	0.05	0.3557	-0.4±0.49	-0.06	0.00	0.7692
Mar 90 – Jul 92	0.0±0.80	0.23	0.05	0.2588	0.1±0.53	-0.28	0.15	**0.0388**
Jan 93 – Nov 93	**0.6±0.50**	1.5	0.80	**0.0002**	**-0.4±0.20**	0.47	0.49	**0.0159**
May 94 – Apr 95	0.3±0.51	-1.1	0.69	**0.0009**	1.1±1.56	1.36	0.12	0.2714
Aug 97 – May 98	**1.3±0.38**	0.32	0.85	**0.0002**	**-0.2±0.16**	-0.10	0.42	**0.0430**

b) La Niña events

	SST (°C)				Chl-a (mg/m³)			
	Average ± std	Slope	R^2	p-value	Average ± std	Slope	R^2	p-value
Sep 83 – Mar 86	0.0±0.78	1.54	0.43	**0.0001**	**-0.9±0.62**	-0.62	0.11	0.0633
Apr 88 – Sep 89	-0.7±0.77	0.66	0.52	**0.0008**	-0.2±0.53	-0.53	0.71	**0.0000**
Aug 95 – Apr 96	0.2±0.69	0.73	0.08	0.4551	**1.1±0.75**	-0.61	0.05	0.5670
Jul 98 – Sep 00	-0.5±0.82	1.06	0.41	**0.0003**	**0.6±0.53**	-0.91	0.72	**0.0000**

Table 3.3. Linear regression analyses were conducted for the Pier surface chlorophyll time series. Table (a) is for annual mean chlorophyll and table (b) is for annual median chlorophyll. Major blooms are included for Var1 (monthly averaged chlorophyll) and Var2 (monthly averaged chlorophyll anomaly), but not for Var3 (monthly averaged chlorophyll) and Var4 (monthly averaged chlorophyll anomaly). Intercept represents a starting point of the linear trend, *i.e.* mean or median values in 1983. Mean1 and Mean2 are averaged vales of the first and last five years, 1983-1987 and 1996-2000, respectively.

(a) Annual mean chlorophyll (mg/m^3)

	R^2	p-value	Slope (mg/m^3/year)	Intercept (mg/m^3)	Mean1 (mg/m^3)	Mean2 (mg/m^3)
Var1.	0.27	0.0271	0.1845	0.8777	1.22	3.41
Var2	0.25	0.0329	0.1774	-1.5511	-1.25	0.87
Var3	0.69	0.0000	0.1087	0.9686	1.15	2.60
Var4	0.66	0.0000	0.1064	-0.9042	-0.74	0.69

(b) Annual median chlorophyll (mg/m^3)

	R^2	p-value	Slope (mg/m^3/year)	Intercept (mg/m^3)	Mean1 (mg/m^3)	Mean2 (mg/m^3)
Var1	0.67	0.0000	0.0744	0.7539	0.88	1.87
Var2	0.49	0.0012	0.0582	-1.1155	-1.04	-0.27
Var3	0.68	0.0000	0.0710	0.7608	0.88	1.83
Var4	0.69	0.0000	0.0719	-1.0062	-0.87	0.07

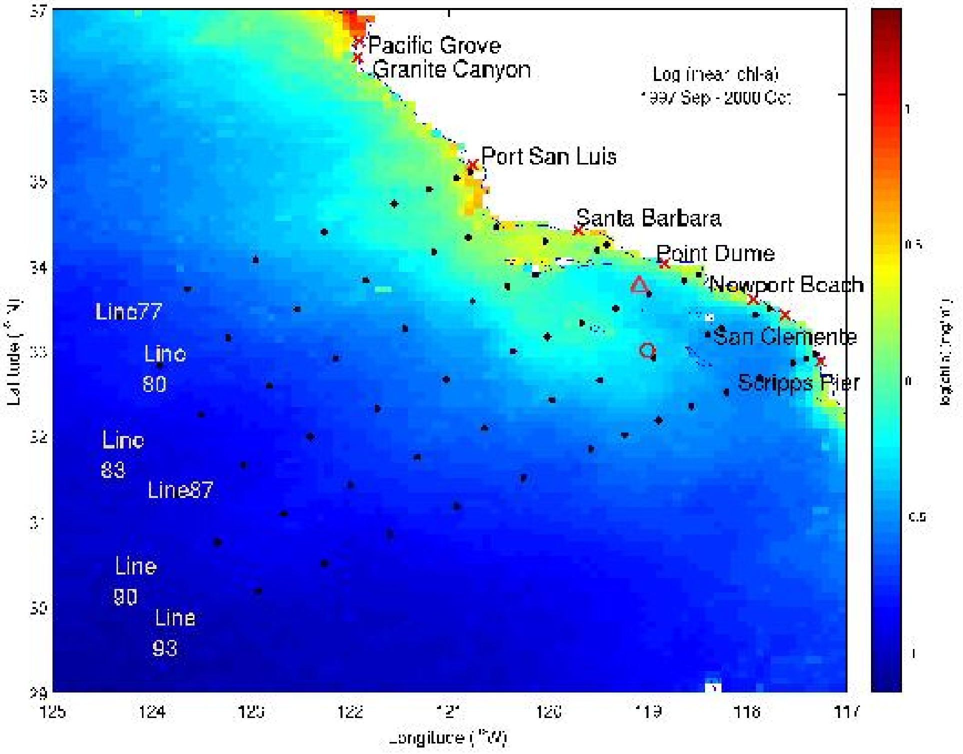


Fig. 3.1. Scripps Pier (32° 52.0'N, 117° 15.4'W) and historical coastal time series stations (red cross, *McGowan et al., 1998*) were marked at the current CalCOFI grid. Red triangle is location of the NDBC buoy 46025. Background color map is 3 year averaged (1997 Sep – 2000 Oct) satellite derived surface chlorophyll.

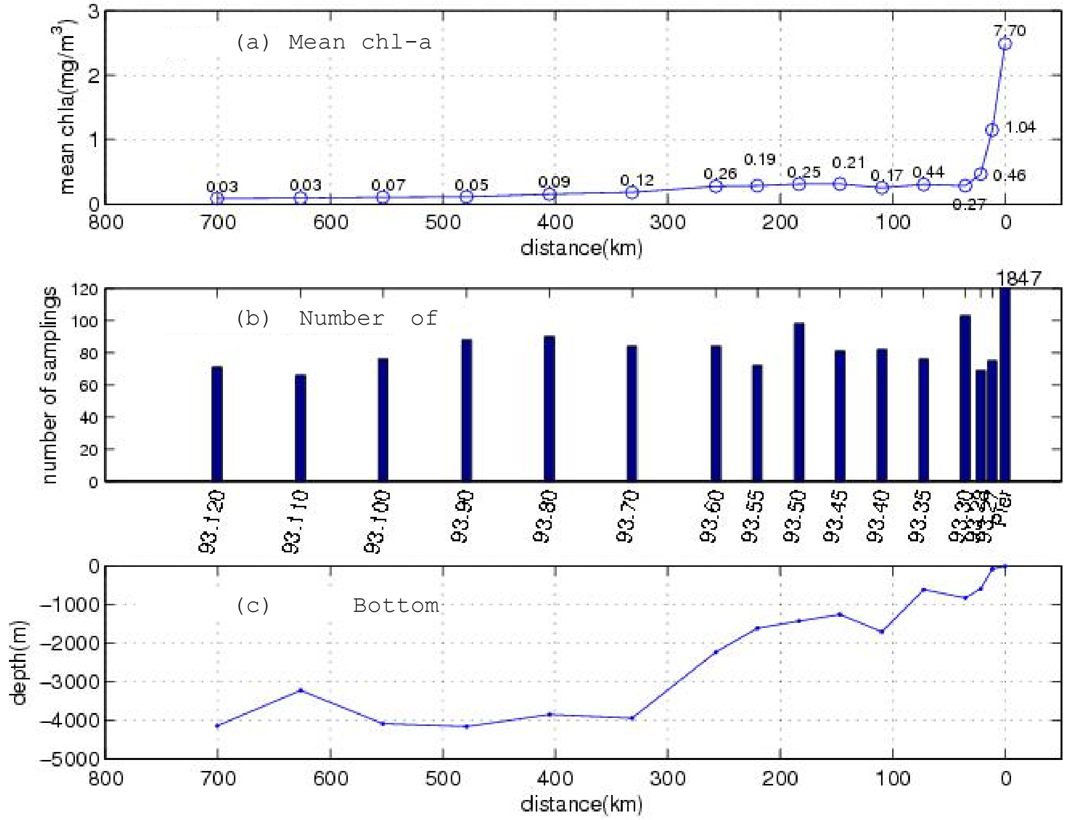


Fig. 3.2. The spatial distribution of average surface chlorophyll (from 1985 to 2000) versus distance from the coastline in the SCB is plotted in (a). Numbers are standard deviations at each station of CalCOFI Line 93 (a). Sample numbers at each station are plotted in (b). One station (93.27) of the Line 93 is on the continental shelf and the shelf break occurs between stations 93.27 and 93.28 (c). The remaining stations are all deeper than 500m. 2-minute Gridded Global Relief Data (ETOPO2, National Geophysical Data Center) was used for bottom topography.

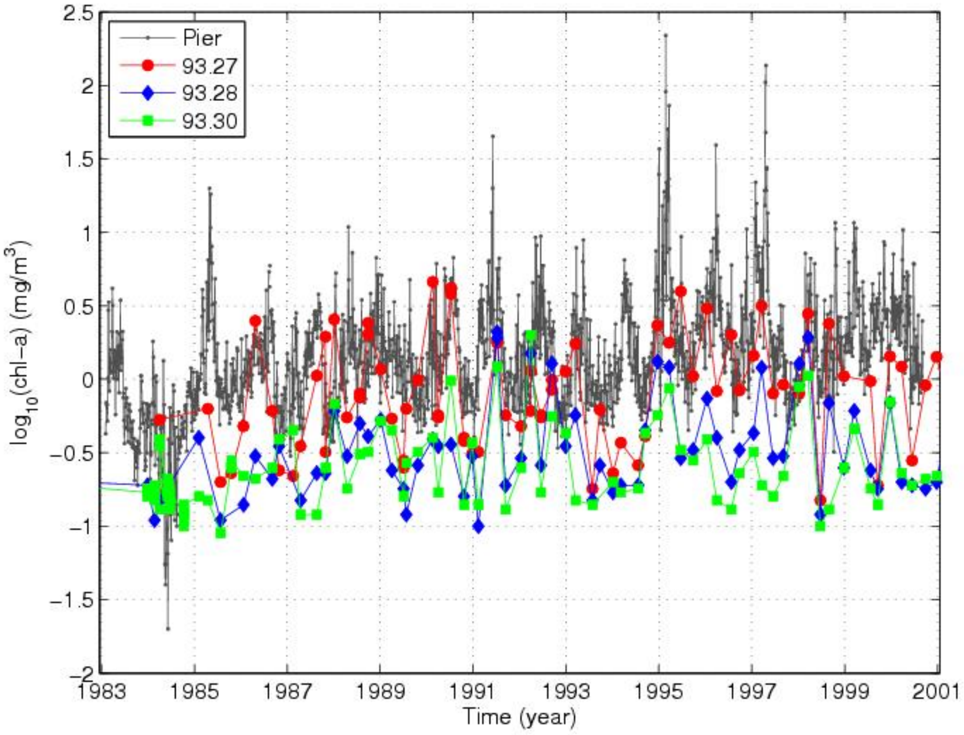


Fig. 3.3. Raw data of surface chlorophyll time series measured at the Scripps Pier (black dots) and nearby CalCOFI stations are plotted. Further stations from the coastline have smaller magnitudes. Notice that the Pier chlorophyll have five pulse events, which have magnitudes that are one or two orders greater than average Pier chlorophyll.

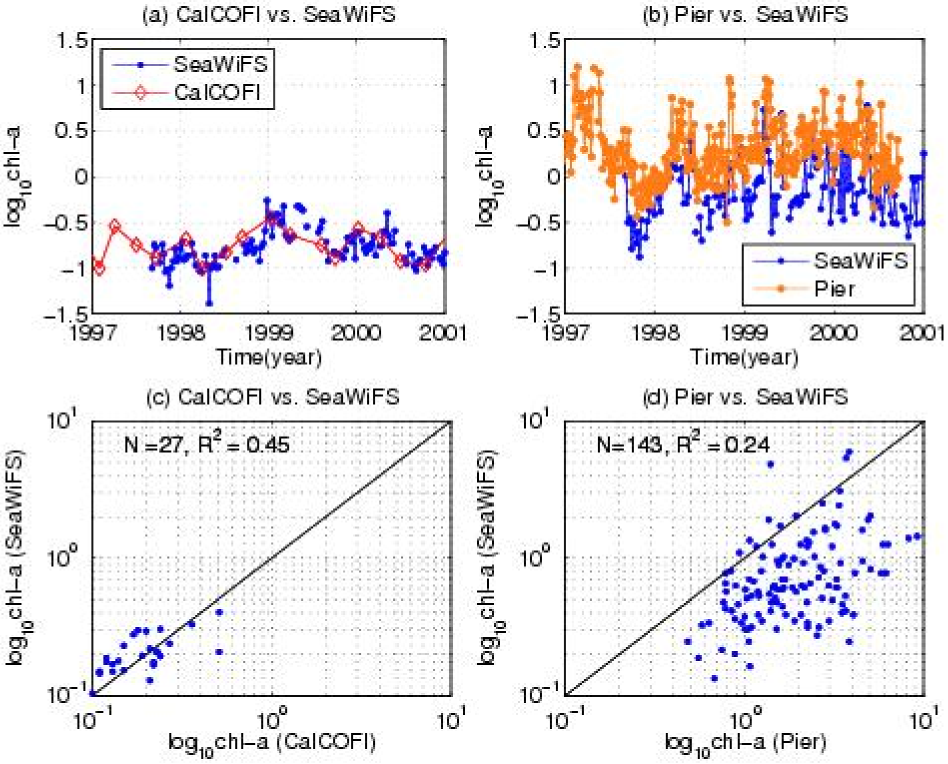


Fig. 3.4. Satellite derived surface chlorophyll (blue dots) was compared with water sampled measurements for offshore (a) and coastal (b) waters. R^2 values of linear regressions for log chlorophyll data are 0.45 (c) and 0.24 (d). For offshore water comparison, chlorophyll data at the CalCOFI station 93.70 were used.

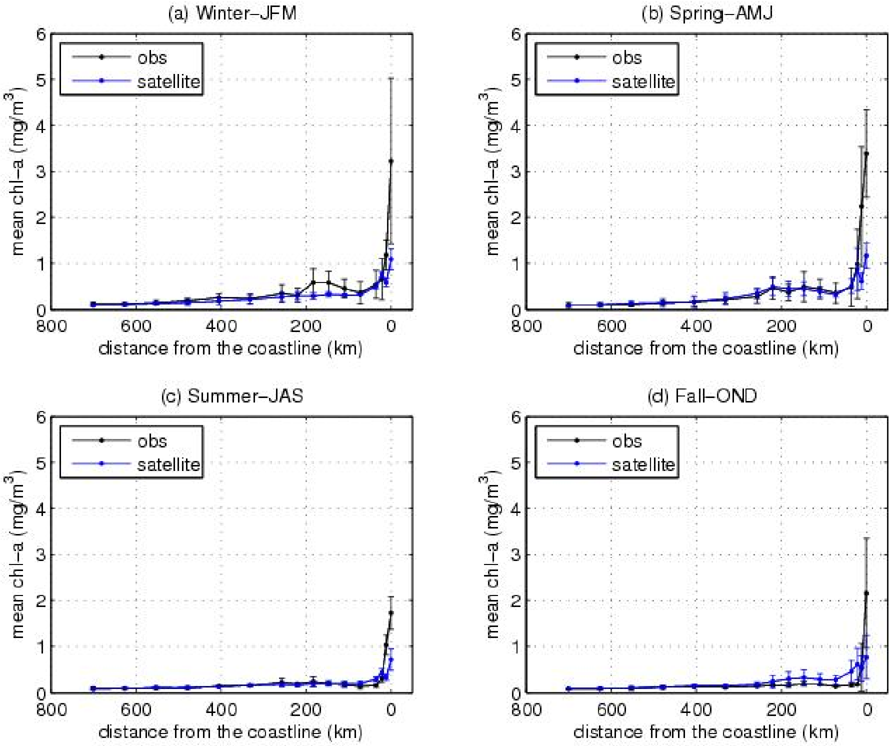
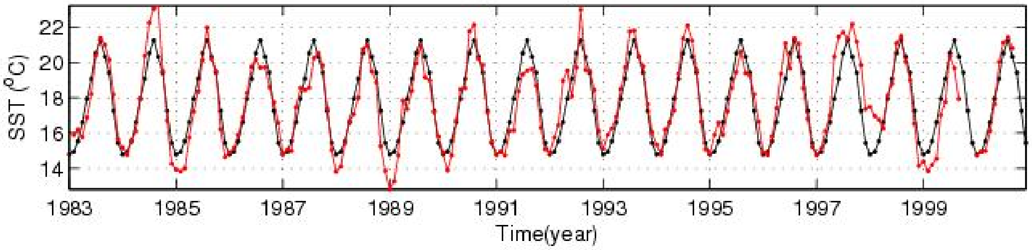
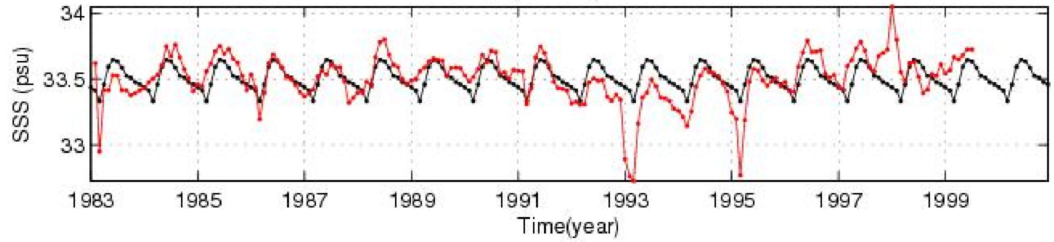


Fig. 3.5. Seasonal mean of satellite derived surface chlorophyll (blue dots, 1997-2000) is compared with CalCOFI data (black dots, 1997-2000) along the Line93. General SeaWiFS algorithm for chlorophyll works well for all seasons at offshore stations deeper than 3000 m and 300 km away from the coastline, but regional algorithms are required for coastal waters especially for winter (JFM) and fall (OND).

(a) Monthly SST



(b) Monthly SSS



(c) Monthly chl–a

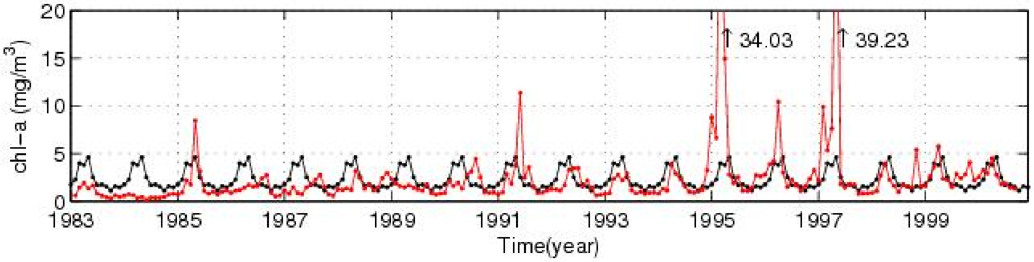


Fig. 3.6. Monthly averaged time series of Pier SST (a), SSS (b), and surface chlorophyll (c). Thin black lines are monthly climatologies between 1983 and 2000 for each variable. The SST (SSS) climatology has an August (June) maximum and January (March) minimum while the chlorophyll climatology has an April maximum and October minimum. The chlorophyll anomalies are more variable than the SST anomalies.

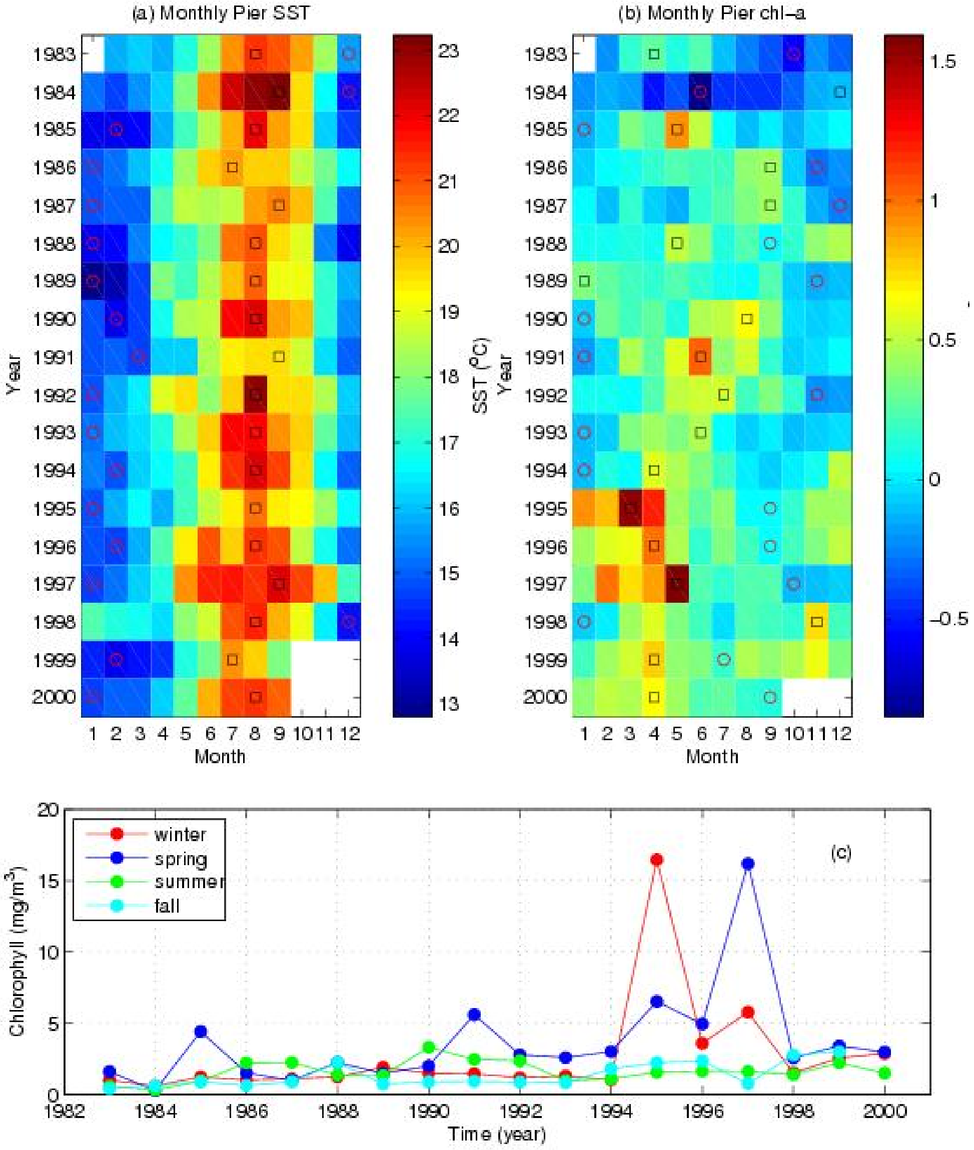


Fig. 3.7. Monthly means of the Pier SST (a) and chlorophyll (b) are plotted as year versus month to examine seasonal cycles for each year. The SST is well explained by the seasonal cycle, but the chlorophyll is not dominated by the seasonal cycle. Black squares are maxima and red circles are minima for each year (a,b). Seasonal means of chlorophyll concentration for each year are plotted in (c). Two unusual average values in 1995 winter and 1997 spring represent major blooms.

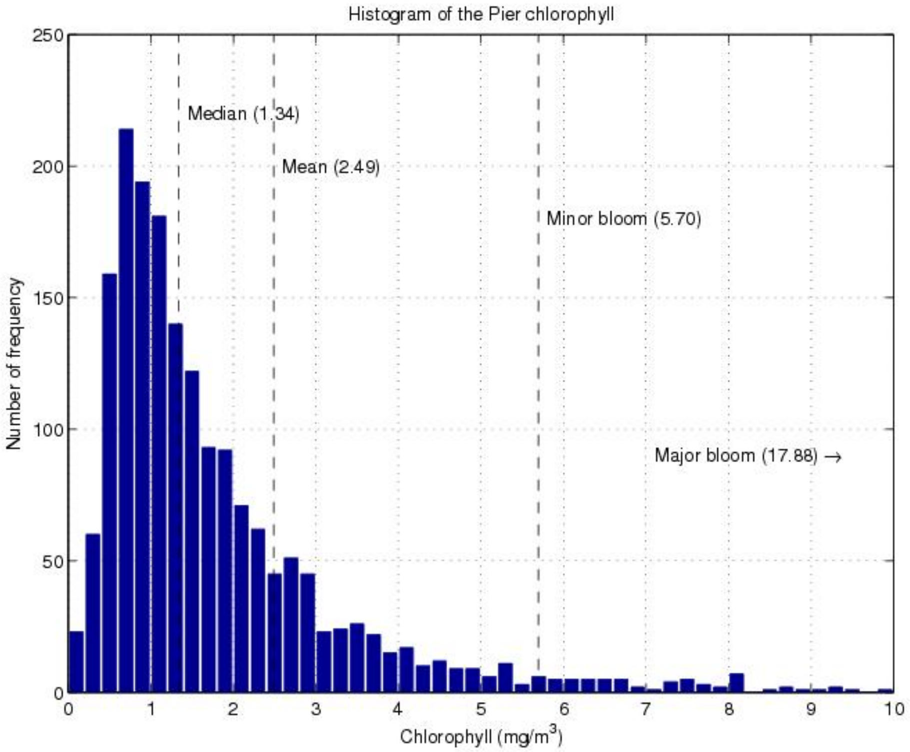
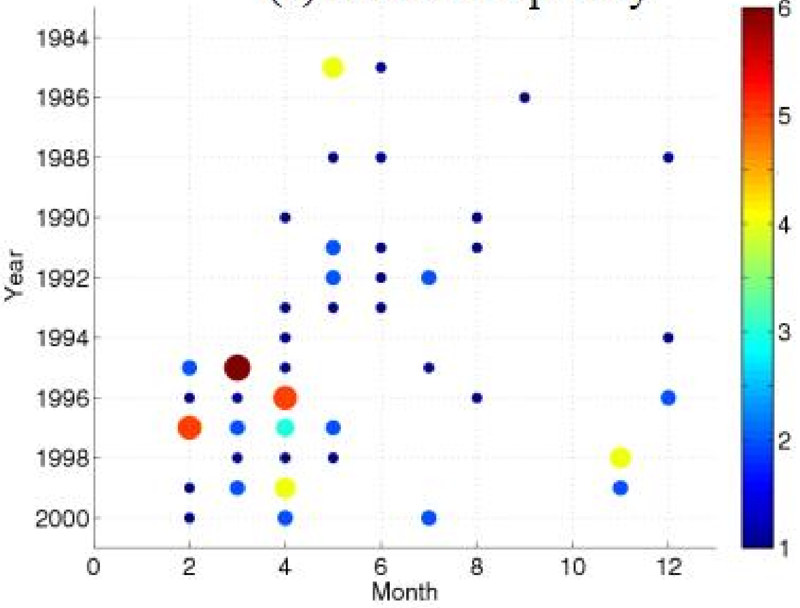


Fig. 3.8. Histogram distribution of the Pier chlorophyll including the five pulse events is positively skewed. Maximum chlorophyll concentration is 218.95 mg/m^3 but longer tail than 10 mg/m^3 is not shown. Median, mean, minor/major bloom thresholds are marked.

(a) Bloom frequency



(b) Bloom magnitude

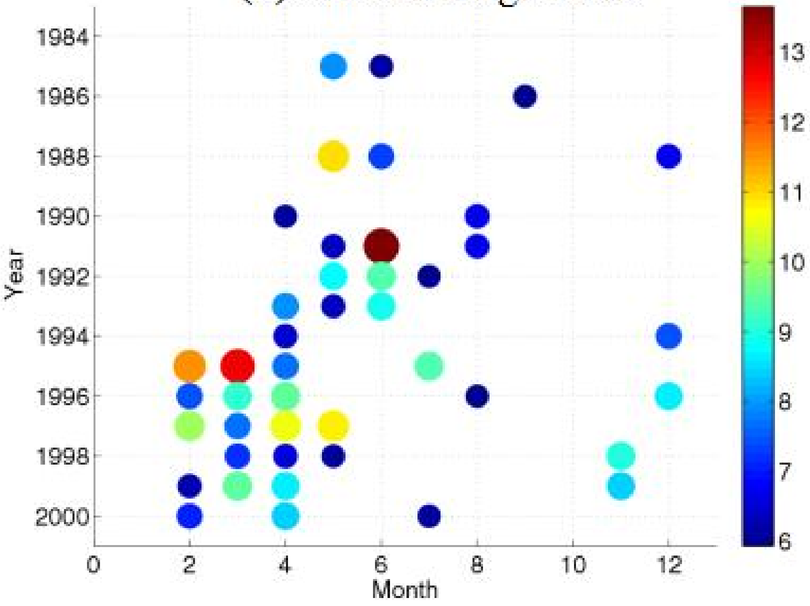
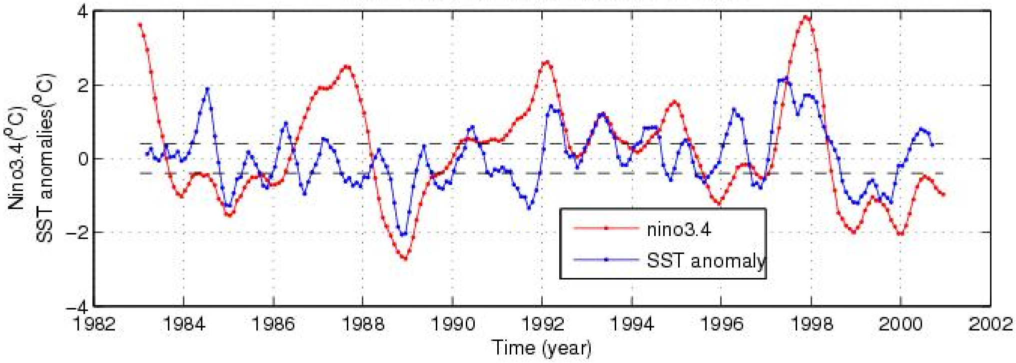


Fig. 3.9. Number of phytoplankton blooms (a) and averaged bloom magnitudes (b) are plotted for each month from 1983 to 2000 using minor blooming thresholds.

(a) Monthly Pier SST anomalies and Nino3.4



(b) Monthly Pier chl−a anomalies and Nino3.4

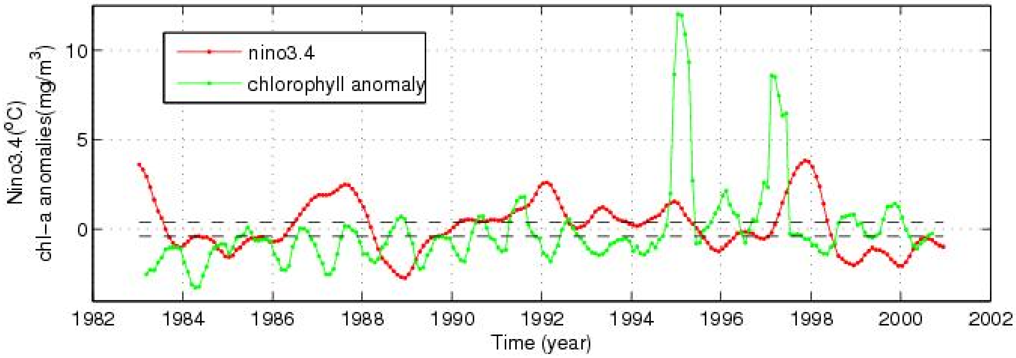


Fig. 3.10. Blue and green lines are 5-month moving averaged SST (a) and chlorophyll (b) anomalies of the Pier data with respect to monthly climatology between 1983 and 2000. Niño 3.4 index has insignificant correlation with the Pier data, but the strong ENSO period from 1997 to 2000 has significant correlation between Niño 3.4 and the Pier data; 0.9 for the SST and –0.7 for the chlorophyll anomalies.

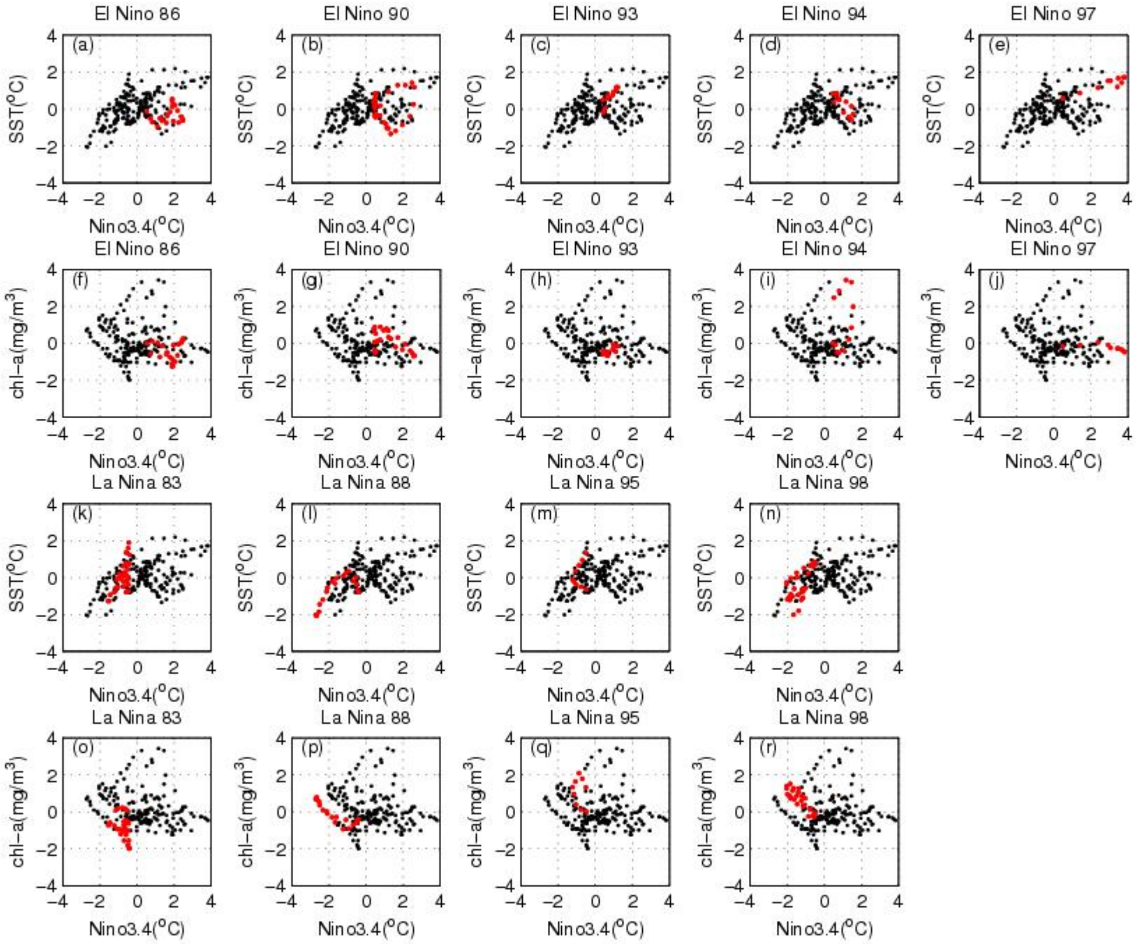


Fig. 3.11. Black dots are scatter plots of Pier SST (chlorophyll) versus Niño 3.4 index in the first (second) and third (fourth) rows from 1983 to 2000. For each El Niño/La Niña event (Table 2) data are marked as red dots in separate plots from left to right. El Niño events are shown in the first two rows (a-j), La Niña events in the last two rows (k-r). These scatter plots show that Pier SST and chlorophyll are not linearly correlated with the Niño 3.4 index. Linear regression statistics for individual events are in Table 2. Major blooms are not plotted, because they range outside of the axes of these plots.

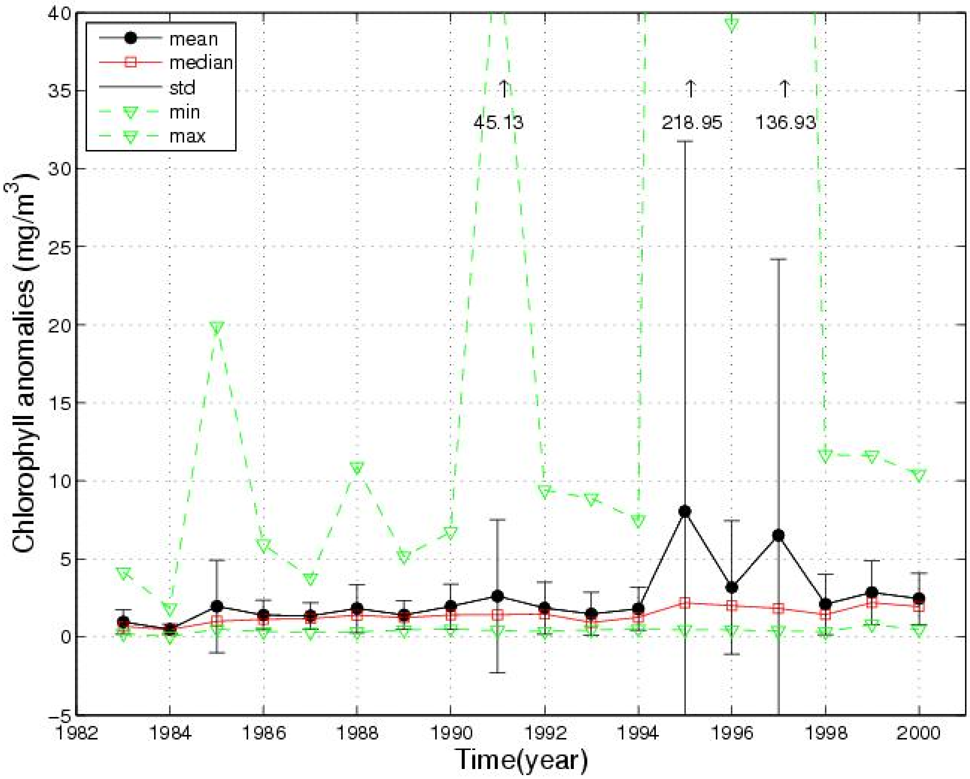


Fig. 3.12. The Pier chlorophyll has an increasing long-term trend from 1983 to 2000. Black dots are annual means (R^2= 0.27); red squares are median values (R^2= 0.67); green triangles are annual maxima and minima; black bars represent one standard deviation. R^2 values increase (0.69 for annual means, 0.67 for medians) if major blooms are excluded for linear regression.

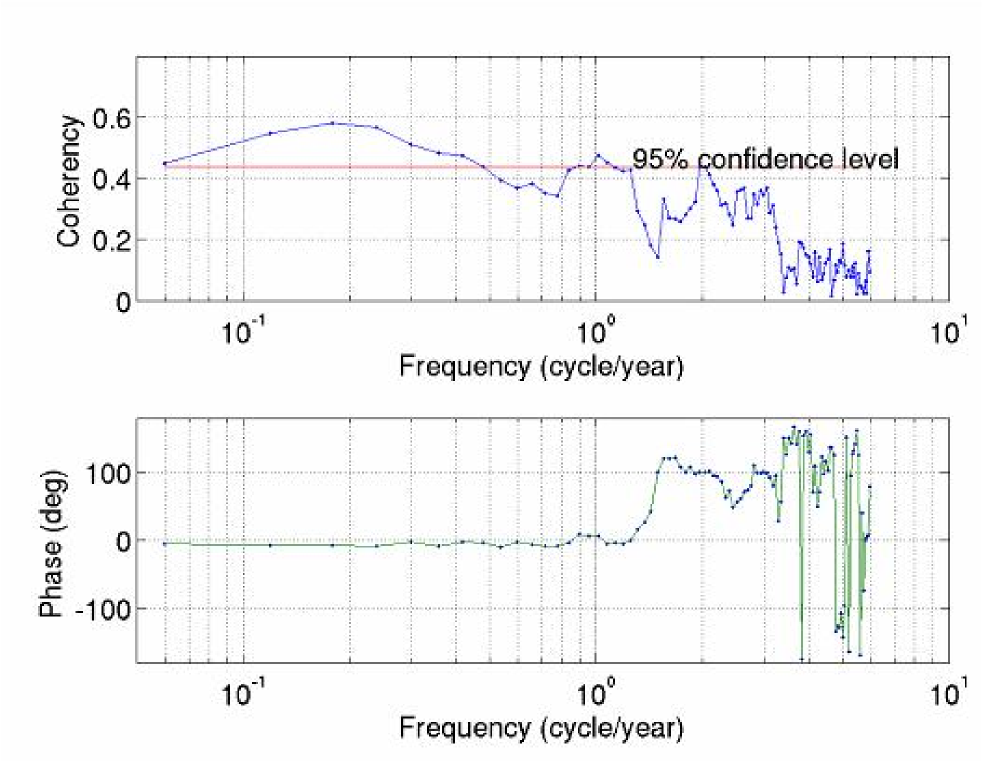


Fig. 3.13. Coherency (top panel) and phase (bottom panel) between the Pier chlorophyll and CalCOFI chlorophyll at the station 93.27. Distance between the Pier and CalCOFI station is about 11.5km. Low frequency band (<0.5 cycle/year) has significant coherency.

References

Allen, W.E., "Red Water" along the West Coast of the United States in 1938, *Science*, *88*, 55-56, 1938.

Allen, W.E., Twenty years statistical studies of marine plankton dinoflagellates of Southern California, *American Midland Naturalist*, *26*, 603-635, 1941.

Barth, J.A., B.A. Menge, J. Lubchenco, F. Chan, J.M. Bane, A.R. Kirincich, M.A. McManus, K.J. Nielsen, S.D. Pierce, and L. Washburn, Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current, *Proceedings of the National Academy of Sciences of the United States of America*, *104* (10), 3719-3724, 2007.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, Climate-driven trends in contemporary ocean productivity, *Nature*, *444* (7120), 752-755, 2006.

Bograd, S.J., and R.J. Lynn, Physical-biological coupling in the California Current during the 1997-99 El Niño-La Niña cycle, *Geophysical Research Letters*, *28* (2), 275-278, 2001.

Bograd, S.J., and R.J. Lynn, Long-term variability in the Southern California Current System, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2355-2370, 2003.

Carter, M., J. McGowan, L. Busse, E. Venrick, and M. Hilbern, Coastal bloom dynamics in Southern California have there been any changes since 1920?, *4th Annual HAB conference*, 2007.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson, Changes in the onset of spring in the western United States, *Bulletin of the American Meteorological Society*, *82* (3), 399-415, 2001.

Chavez, F.P., P.G. Strutton, C.E. Friederich, R.A. Feely, G.C. Feldman, D.C. Foley, and M.J. McPhaden, Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño, *Science*, *286* (5447), 2126-2131, 1999.

Chelton, D.B., P.A. Bernal, and J.A. Mcgowan, Large-Scale Interannual Physical and Biological Interaction in the California Current, *Journal of Marine Research*, *40* (4), 1095-1125, 1982.

Chelton, D.B., and R.E. Davis, Monthly Mean Sea-Level Variability Along the West-Coast of North-America, *Journal of Physical Oceanography*, *12* (8), 757-784, 1982.

Darecki, M., and D. Stramski, An evaluation of MODIS and SeaWiFS bio-optical algorithms in the Baltic Sea, *Remote Sensing of Environment*, *89* (3), 326-350, 2004.

Gregg, W.W., N.W. Casey, and C.R. McClain, Recent trends in global ocean chlorophyll, *Geophysical Research Letters*, *32* (3), 2005.

Gregg, W.W., and M.E. Conkright, Decadal changes in global ocean chlorophyll, *Geophysical Research Letters*, *29* (15), 2002.

Haldorson, L., M. Pritchett, D. Sterritt, and J. Watts, Abundance Patterns of Marine Fish Larvae During Spring in a Southeastern Alaskan Bay, *Fishery Bulletin*, *91* (1), 36-44, 1993.

Hayward, T.L., and E.L. Venrick, Nearsurface pattern in the California Current: coupling between physical and biological structure, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *45* (8-9), 1617-1638, 1998.

Henson, S.A., and A.C. Thomas, Phytoplankton scales of variability in the California Current System: 1. Interannual and cross-shelf variability, *Journal of Geophysical Research-Oceans*, *112*, doi:10.1029/2006JC004039, 2007.

Hirawake, T., T. Odate, and M. Fukuchi, Long-term variation of surface phytoplankton chlorophyll a in the Southern Ocean during 1965-2002, *Geophysical Research Letters*, *32* (5), 2005.

Kahru, M., and B.G. Mitchell, Empirical chlorophyll algorithm and preliminary SeaWiFS validation for the California Current, *International Journal of Remote Sensing*, *20* (17), 3423-3429, 1999.

Karl, D.M., R. Letelier, D. Hebel, L. Tupas, J. Dore, J. Christian, and C. Winn, Ecosystem Changes in the North Pacific Subtropical Gyre Attributed to the 1991-92 El-Niño, *Nature*, *373* (6511), 230-234, 1995.

Kim, H.-J., and A.J. Miller, Did the Thermocline Deepen in the California Current after the 1976/77 Climate Regime Shift?, *Journal of Physical Oceanography*, *37* (6), 1733-1739, 2007.

Legaard, K.R., and A.C. Thomas, Spatial patterns in seasonal and interannual variability of chlorophyll and sea surface temperature in the California Current, *Journal of Geophysical Research-Oceans*, *111* (C06032), doi:10.1029/2005JC003282, 2006.

Lentz, S.J., and D.C. Chapman, The importance of Nonlinear cross-shelf momentum flux during wind-driven coastal upwelling, *Journal of Physical Oceanography*, *34* (11), 2444-2457, 2004.

McClain, C.R., S.R. Signorini, and J.R. Christian, Subtropical gyre variability observed by ocean-color satellites, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *51* (1-3), 281-301, 2004.

McGowan, J.A., S.J. Bograd, R.J. Lynn, and A.J. Miller, The biological response to the 1977 regime shift in the California Current, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2567-2582, 2003.

McGowan, J.A., D.R. Cayan, and L.M. Dorman, Climate-ocean variability and ecosystem response in the northeast Pacific, *Science*, *281* (5374), 210-217, 1998.

Moloney, C.L., and J.G. Field, General allometric equations for rates of nutrient uptake, ingestion, and respiration in plankton organisms, *Limnology and Oceanography*, *34* (7), 1290-1299, 1989.

Pennington, J.T., and F.P. Chavez, Seasonal fluctuations of temperature, salinity, nitrate, chlorophyll and primary production at station H3/M1 over 1989-1996 in Monterey Bay, California, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *47* (5-6), 947-973, 2000.

Penuelas, J., and I. Filella, Phenology - Responses to a warming world, *Science*, *294* (5543), 793-795, 2001.

Reid, F.M.H., C.B. Lange, and M.M. White, Microplankton Species Assemblages at the Scripps Pier from March to November 1983 During the 1982-1984 El-Niño Event, *Botanica Marina*, *28* (10), 443-452, 1985.

Reid, P.C., M. Edwards, H.G. Hunt, and A.J. Warner, Phytoplankton change in the North Atlantic, *Nature*, *391* (6667), 546-546, 1998.

Roemmich, D., Ocean Warming and Sea-Level Rise Along the Southwest United-States Coast, *Science*, *257* (5068), 373-375, 1992.

Roemmich, D., and J. McGowan, Climatic Warming and the Decline of Zooplankton in the California Current, *Science*, *267* (5202), 1324-1326, 1995.

Strub, P.T., and C. James, Altimeter-derived surface circulation in the large-scale NE Pacific Gyres. Part 2: 1997-1998 El Niño anomalies, *Progress in Oceanography*, *53* (2-4), 185-214, 2002.

Strub, P.T., C. James, A.C. Thomas, and M.R. Abbott, Seasonal and Nonseasonal Variability of Satellite-Derived Surface Pigment Concentration in the California Current, *Journal of Geophysical Research-Oceans*, *95* (C7), 11501-11530, 1990.

Sugihara, G., and R.M. May, Nonlinear Forecasting as a Way of Distinguishing Chaos from Measurement Error in Time-Series, *Nature*, *344* (6268), 734-741, 1990.

Thomas, A.C., F. Huang, P.T. Strub, and C. James, Comparison of the Seasonal and Interannual Variability of Phytoplankton Pigment Concentrations in the Peru and California Current Systems, *Journal of Geophysical Research-Oceans*, *99* (C4), 7355-7370, 1994.

Tont, S.A., Variability of Diatom Species Populations - from Days to Years, *Journal of Marine Research*, *45* (4), 985-1006, 1987.

Torrey, H.B., An unusual occurrence of Dinoflagellata on the California coast, *American Naturalist*, *36*, 187-192, 1902.

Townsend, D.W., Comparison of Inshore Zooplankton and Ichthyoplankton Populations of the Gulf of Maine, *Marine Ecology-Progress Series*, *15* (1-2), 79-90, 1984.

Trenberth, K.E., The definition of El Niño, *Bulletin of the American Meteorological Society*, *78* (12), 2771-2777, 1997.

Ware, D.M., and R.E. Thomson, Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific, *Science*, *308* (5726), 1280-1284, 2005.

Winant, C.D., and C.E. Dorman, Seasonal patterns of surface wind stress and heat flux over the Southern California Bight, *Journal of Geophysical Research-Oceans*, *102* (C3), 5641-5653, 1997.

Chapter 4 Decadal variability of density and nitrate, with biological implications

ABSTRACT

Upper-ocean nitrate concentration has been measured regularly in CalCOFI since 1984, but its variability in earlier decades, since 1949, is not well known. In order to reconstruct nitrate variability in the earlier decades of CalCOFI, an analysis of the relation between nitrate and density is performed.

Vertical sections of density from 10-100m depth in CalCOFI have similar characteristics to nitrate sections on seasonal timescales, and they are both mainly driven by seasonal wind stress in the southern California Current (SCC). The leading principal components (PC's) of density (39%) and nitrate (36%) seasonal anomalies for the sections measured from 1984-2006 are coherent. A combined empirical orthogonal function (EOF) analysis of density and nitrate anomalies reveals that isopycnals shoal and the upper-ocean nutrient content increases from the early 1990's to 2006 at low frequency, which is consistent with the observed macrozooplankton displacement volume biomass increase after the early 1990's.

Since the 1st PC of upper-ocean density is correlated with the upper-ocean nitrate content, density can be used as a quantitative proxy for nitrate in earlier decades of CalCOFI. The nitrate proxy provides a new perspective on the bottom-up forcing of the long-term changes in macrozooplankton observed in CalCOFI. PC1 of the 10m-100m density anomalies from the 56-year CalCOFI sections explains 36% of the variance, which is comparable to the variance explained in the shorter 1984-2006 time period and serves as the nitrate proxy. The nitrate proxy PC1 decreases from 1950 to the early

1990’s, but increases afterwards, which is a tendency that is similar to that exhibited by the surface chlorophyll and displacement volume macrozooplankton biomass time series in CalCOFI, supporting the idea that bottom-up forcing by the physical climate system drives the changes in the zooplankton.

The nitrate proxy PC1 has a higher correlation with the Pacific Decadal Oscillation (PDO) index rather than with the North Pacific Gyre Oscillation (NPGO) index, indicating that the forcing is not local to CalCOFI but associated with basin-scale climate processes.

4.1 Introduction

Wind stress and wind stress curl play an important role in upper-ocean dynamics and ecosystem response in the SCB. Both classical coastal upwelling driven by Ekman transport and open-ocean Ekman pumping induced by cyclonic wind stress curl force upper ocean isopycnal deepening and shoaling over the seasonal cycle in the southern California Current (SCC), These processes cause nutrient level changes in the euphotic zone, which alters upper ocean primary production.

The seasonal cycle of isopycnals in the California Cooperative Fisheries Investigations (CalCOFI) dataset is clearly associated with the seasonal-cycle wind stress pattern (*Winant and Dorman* [1997]). Although many CalCOFI cruise report maps show that density and nitrate have similar patterns in the upper ocean (e.g., CalCOFI 2005), the nitrate patterns observed in CalCOFI that correspond to seasonal isopycnal changes have not been analyzed in detail. Moreover, the interannual and longer-term variability of the isopycnal-nitrate relationship has only recently begun to be examined [*McGowan et al.*, 2003; *Rykaczewski and Checkley*, 2008]. A better understanding of long-term changes in nitrate in CalCOFI may help to explain the long-term decline in zooplankton displacement volume biomass reported by *Roemmich and McGowan* [1995] and the long-term stability of the zooplankton carbon biomass estimates identified by *Lavaniegos and Ohman* [2007].

We consider here the issue of whether nitrate and density exhibit a consistent spatial and temporal relationship in the CalCOFI for both their seasonal cycle and their long-term variability. Nitrate has only been measured regularly in CalCOFI since 1984, while density has been measured since 1949. If nitrate and density can be shown to exhibit a close relationship during the time period 1984-2006, we may be able to exploit this relationship to estimate the upper-ocean nitrate variability using density as a proxy in the time period from 1949-1983, when nitrate was not well measured. The results may be able to provide a new perspective on the idea that bottom-up forcing by the physical climate system drives the changes in the zooplankton biomass.

McGowan et al. [2003] analyzed 12^{o}C isothermal depths and assumed that they represented 10 µM/L iso-nitrate nutricline depths using the 50-year CalCOFI data (1950 – 2000) in attempting to explain the changes in the ecosystem observed across the 1976-77 climate regime shift. However, the upper-ocean intensified warming [*Bograd and Lynn*, 2003; *Di Lorenzo et al.*, 2005; *Kim and Miller*, 2007] deepens this isothermal depth inevitably after the regime shift, causing this isothermal depth to correspond to a different magnitude of nitrate [*Kim and Miller*, 2007]. Thus the 12^{o}C isothermal depth and 10 µM/L iso-nitrate depth is not linearly correlated across the climate regime shift and cannot be used as a long-term proxy for nitrate.

Rykaczewski and Checkley [2008] show a close linkage between wind stress curl, analyzed by down-scaling reanalysis wind data, and biological changes, including 10 m chlorophyll of the CalCOFI data and Pacific sardine biomass in the SCB. They defined nutricline depth as the 1 µM/L nitrate depth, which limits their nutricline analysis to the period after 1984 when nutrient and chlorophyll measurements started to be sampled routinely by the CalCOFI program.

Thus the relationships between wind-stress forcing, isopycnal depth, nutricline depth, primary production and zooplankton biomass in the CalCOFI dataset are still unclear. In this study, the seasonality of density and nitrate sections is first examined, and then EOF analyses are performed on two-dimensional seasonal density and nitrate anomalies. The covariability of these two water properties identified using the CalCOFI dataset is then used to attempt to better understand the biological variability over decadal time scales in the SCB. Temporal variability of the leading principal component of density, which serves as a proxy for nitrate, is then compared to physical climate indices, namely, the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997] and the North Pacific Gyre Oscillations (NPGO) [*Di Lorenzo et al.*, 2008]. This links the local response to previous studies that show that many biological changes over basin scales, *e.g.* zooplankton [*Lavaniegos and Ohman*, 2003] and Pacific salmon production [*Mantua et al.*, 1997], have significant correlation with the PDO index.

4.2 Data analysis

4.2.1 CalCOFI density and nitrate sections

Hydrographic surveys have been conducted in the SCC since 1949 by the CalCOFI program (http://calcofi.org), but major nutrients and chlorophyll measurements have only been routinely sampled since 1984. To examine temporal and spatial variability of density and nitrate, 88 cruises from 1985 to 2006 are selected out of the 331 cruises from 1950 to 2006. Selected cruises have both density and nitrate profiles at 13 stations out of 15 stations along CalCOFI Line 93 (Fig. 4.1).

Density profiles were calculated from temperature and salinity profiles for each cruise. Density and nitrate profiles at each station were vertically interpolated to obtain 1 m resolution and then resampled every 10 m. Only data in the upper 100 m were used for the EOF analysis since euphotic depth is generally shallower than 100 m and most photosynthesis occurs above the euphotic depth.

Density (M1) and nitrate (M2) matrices from 1985 to 2006 were obtained for EOF analyses. They have 150 time series at 10 different depths (from 10 m to 100 m with 10 m interval) and 15 stations of Line 93. Two more density matrices (M3, M4) were obtained with 123 (155) cruises along Line 93 (Line 90). These two density matrices include selected cruises from 1950 to 2006 that have temperature and salinity profiles (but no nitrate profiles prior to 1985).

4.2.1 PDO and NPGO indices

The principle component of the 1st EOF of SST monthly anomalies in the North Pacific is well known as the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997; *Mantua and Hare*, 2002]. The monthly PDO index was obtained (http://jisao.washington.edu/pdo/PDO.latest) and compared with density and nitrate variability in the CalCOFI grid.

The principle component of the 2nd EOF of SST is known as the Victoria mode or the North Pacific Decadal Oscillation (NPGO) [*Di Lorenzo et al.*, 2008]. *Di Lorenzo et al.* [2008] show that surface salinity, chlorophyll, and nitrate anomalies in the CalCOFI data are significantly correlated with the NPGO index (http://eros.eas.gatech.edu/npgo/) whereas sea surface temperature is highly correlated with the PDO index.

4.3 Results

4.3.1 Upper-ocean nitrate content

An isothermal depth is often suggested to be a proxy of iso-nitrate depth [*Hayward and Venrick*, 1998; *Bograd and Lynn*, 2001; *McGowan et al.*, 2003]. To examine the relationship between nitrate and temperature, two variables, the water depth with a nitrate concentration of 10 μM/L (D_{10NO3}) and the temperature at the D_{10NO3} (T_{10NO3}), are calculated at 15 stations of CalCOFI Line 93(Fig. 4.2). The D_{10NO3} denotes a water column thickness of the upper ocean with a nitrate concentration less than 10 μM/L, i.e. nutrient-poor water ([NO3] < 10 μM/L) occupies the upper ocean from the surface to the D_{10NO3}. D_{10NO3} tends to increase, and T_{10NO3} decrease, as stations are further away from the coastline (Fig. 4.2). The furthest offshore station of Line 93 (93.120, Fig. 4.1) has a roughly 4 times larger D_{10NO3} than the closest station to the coastline (93,27, Fig. 4.1), indicating lower productivity in the offshore regions.

Fig. 4.2 reveals that the iso-nitrate depth, D_{10NO3}, is not significantly correlated with temperature at the depth of D_{10NO3}. Therefore a single isothermal is not appropriate for a long-term proxy of nitrate availability in the upper ocean, and a better proxy for nitrate must be identified. As *Kim and Miller* [2007] showed, the upper-ocean warming over decadal time scales in CalCOFI forces the isothermal depth to deepen so that the warmed water does not necessarily represent less nutrient. *They* show [2007] that the 12°C water deepened, but it in fact has higher nitrate concentration across the 1976-77 climate regime shift at offshore CalCOFI stations, which is consistent with the lack of a relationship found here.

4.3.2 Seasonal cycle of density and nitrate sections

Both wind stress and wind stress curl play an important role in driving upper-ocean dynamics in the SCB [*Winant and Dorman*, 1997; *Pickett and Paduan*, 2003]. In spring, offshore winds strengthen and inshore winds from the line between Pt. Conception, CA and Ensenada, Mexico, are weak [*Winant and Dorman*, 1997]. Consequently, strong cyclonic wind stress curl develops in the SCB and Ekman pumping is induced, which might bring cold dense nutrient-rich water to the euphotic zone. In fall, the cyclonic wind stress curl weakens and the magnitude of upwelling-favorable wind is also reduced [*Winant and Dorman*, 1997]. Seasonal averages of alongshore wind stress measured along Line 93 (Fig. 4.1) by CalCOFI cruises show patterns consistent with *Winant and Dorman* [1997] (Fig. 4.3).

Seasonal averages of density (Fig. 4.4) and nitrate (Fig. 4.5) sections show that isopycnals and upper-ocean nitrate content variations are consistent with forcing by seasonal patterns of longshore wind and wind-stress curl. Isopycnals are lifted in spring and summer and simultaneously nitrate contours are lifted (Fig. 4.4bc, and Fig. 4.5bc). The lifting of isopycnals is prominent shoreward of the offshore maximum wind axis, about 200 km from the coastline. This upper-ocean feature in spring and summer might be related to the phytoplankton spring blooms. In fall and winter, isopycnals and nitrate contours deepen due to weakening of wind stress curl (Fig. 4.4ad, and Fig. 4.5ad). *Di Lorenzo* [2003] shows how upper-ocean seasonal circulation in the SCC is governed by alongshore wind stress and wind stress curl using numerical modeling studies.

4.3.3 Density and nitrate seasonal anomalies

To examine the temporal and spatial patterns of seasonal density and nitrate anomalies, EOF analyses were conducted for 4 matrices (M1 – M4) as described in section 4.2. Low frequency variability of the leading principal component of density anomalies fluctuates with periods of approximately 7-8 years (Fig. 4.6a). The principal component of the 1st EOF in spring (Mar – June), marked as red dots, shows an increasing trend between 1992 and 2006, which corresponds to the time period when zooplankton biomass stopped declining and started increasing as discussed later. A two-dimensional map of the first EOF of M1 shows that its structure decreases from the coast to offshore (Fig. 4.6c), which implies that density variability at coastal areas inside of the maximum wind axis is larger than further offshore. The 1st principal component of nitrate seasonal anomalies (Fig. 4.7a) corresponds to that of the seasonal density anomalies (Fig. 4.6a).

The1st principal components show that isopycnals shoal and nitrate contours rise from 1985 to 2006 at low frequency, which implies that more nutrients are available in the upper ocean during the last several years compared to the 1980's. This is consistent with the analysis of [*Rykaczewski and Checkley*, 2008] who found an increasing trend in 50m density, 1mgm/m**3 nitrate depth, and 10m chlorophyll over this same time period. This increase in nitrate might be a primary reason why surface chlorophyll at the Scripps Pier increases from 1983 to 2000, as does the CalCOFI surface chlorophyll (Chapter 3).

The leading principal components (Fig. 4.6a, Fig. 4.7a) of M1 (22-year density data) and M2 (22-year nitrate data) are significantly correlated. Therefore, a combined EOF analysis (Fig. 4.8) has been performed on M1 and M2 seasonal anomalies to better detect the covariability of the density and nitrate fields. The leading principal component of the combined EOF (Fig. 4.8ace) shows that isopycnals and iso-nitrate contours shoal at low frequency from 1985 to 2006, which might bring increased amount of nitrate to the upper ocean, consequently resulting in more primary production.

The 2nd EOF's of density and nitrate seasonal anomalies (Fig. 4.6cd, Fig. 4.7cd) show maximum changes at CalCOFI station 93.60 (31°N 51', 119°W 34') where the maximum positive wind stress curl in spring and summer occurs along Line 93. Thus the 2nd EOF's appears to be driven by local wind stress curl changes, while the 1st EOF's of density and nitrate seasonal anomalies appear to be associated with basin-scale wind stress curl pattern.

4.3.4 Multi-decadal changes of density sections

Hydrographic surveys and zooplankton measurements have been conducted by CalCOFI program since 1949. One of the important results observed by the CalCOFI program is a long-term trend, from 1950-1993, of decreasing zooplankton displacement volume biomass and concomitant warming of the upper-ocean in the SCB [*Roemmich and McGowan*, 1995]. Lavaniegos and Ohman (2007), in contrast, showed that zooplankton carbon biomass exhibited no significant long-term trend from 1951-2005. Chlorophyll, on the other hand, has been routinely sampled only since 1984, so that there is a missing link between primary production and zooplankton over the decadal time scales of CalCOFI.

The combined EOF analysis (Fig. 4.8) reveals that two-dimensional variability of density and nitrate anomalies along Line 93 is coherent for two decades. Positive density anomalies (shoaling of isopycnals) correspond to positive nitrate anomalies (shoaling of iso-nitrate contours) and vice versa. Thus, the leading principal component of seasonal density anomalies (PC1) can be used as a proxy for upper ocean nutrient content in the SCB. High nutrient content might cause high primary production.

Hydrographic surveys that have both temperature and salinity profiles have been selected to calculate density for more than five decades along Line 93 (M3, Fig. 4.9), which is the closest CalCOFI Line to the Scripps Pier, and Line 90 (M4, Fig. 4.10), north of the Line 93. Line 90 has been sampled more regularly than Line 93.

The 1st principal component for M3 and M4 shows deepening of isopycnals from 1950 to the early 1990's and then shoaling of isopycnals afterwards (Fig. 4.9, Fig. 4.10). The shoaling of isopycnals during the last two decades as detected by this long time period EOF analysis corresponds to the shoaling also detected in the shorter time period EOF analysis of density and nitrate. Therefore, the leading principal component of seasonal density anomalies (PC1) may be a useful indicator of primary production.

4.3.5 Relation to surface chlorophyll

Nearshore stations in the CalCOFI grid have higher chlorophyll magnitudes than offshore stations. The 22-year averages of depth-integrated chlorophyll concentrations at each station of Line 90 and 93 (Fig. 4.11) show that stations on the continental shelf have the highest magnitudes, which suggests driving by coastal upwelling by Ekman transport or mixing processes associated with topography. A second maximum chlorophyll concentration occurs in the area with the highest positive wind stress curl in spring (Chelton, 1982). This area corresponds to the 2nd EOF of density and nitrate anomalies

(Fig. 4.6d and Fig. 4.7d). Unfortunately the vertical sampling of the chlorophyll is not adequate to compare to the vertical structure of the density and nitrate changes studied here. However, notice that the 10-m chlorophyll changes identified by [*Rykaczewski and Checkley*, 2008] are correlated with the 1st principal components of density and nitrate.

4.3.6 Relation to climate indices

The PDO index is often significantly correlated with biological variables [*Mantua et al.*, 1997; *Mantua and Hare*, 2002; *McGowan et al.*, 2003; *Schneider and Cornuelle*, 2005] as well as physical variables like SST, sea level, and wind stress [*Schneider and Cornuelle*, 2005; *Mestas-Nunez and Miller*, 2006]. For example, *Henson and Thomas* [2007] show that interannual surface chlorophyll variance has a significant negative correlation with the PDO index using a daily SeaWiFS dataset.

The leading principal components of density anomalies (PC1s) along Line 90 and Line 93 are also correlated with the PDO index (Fig. 4.12). Annual means of the PC1s have correlations of 0.75 (Line 90) and 0.66 (Line 93) with the PDO index, but they have insignificant correlations with the NPGO index (Fig. 4.12). This implies that the upper-ocean dynamics in the SCB is influenced by the basin-scale surface atmospheric forcing associated with the PDO pattern.

4.3.7 Long-term trend of physical changes and biological implications

Long-term trends of upper-ocean warming [*Roemmich and McGowan*, 1995; *Di Lorenzo et al.*, 2005; *Kim and Miller*, 2007], zooplankton displacement volume biomass

[*Roemmich and McGowan*, 1995], and surface chlorophyll [*Kim et al.*, 2008; *Rykaczewski and Checkley*, 2008] have been observed in the CalCOFI dataset. These trends are statistically significant; however, they cover different time spans (Fig. 4.14). We compare these trends with the density proxy for nitrate variations over the same time periods.

The increasing warming and decreasing macro-zooplankton displacement volume biomass trends from 1950 to 1994 [*Roemmich and McGowan*, 1995] are consistent with the decreasing PC1 (the leading principal component of seasonal density anomalies, Fig. 4.14), which indicates deepening of isopycnals and reduced iso-nitrate contours (Fig. 4.15). Since approximately 1994, however, the macrozooplankton has stopped decreasing, and instead exhibits an increasing trend from 1992 to 2006 (Fig. 4.14). This increasing trend is consistent with the increasing trend of PC1 of density (and nitrate), suggesting increase availability of nutrients and primary production (Fig. 4.14). Since these two back-to-back trends nearly compensate, there is no strong trend evident in PC1 over the period 1950-2006. This is more consistent with the estimates of nearly constant zooplankton carbon biomass over this time period observed by *Lavaniegos and Ohman* [2007] than the overall drop in zooplankton displacement volume biomass seen in Fig. 4.14 and in *Lavaniegos and Ohman* [2007].

Chlorophyll also exhibits an increasing trend at the Scripps Pier from 1983 to 2000 [*Kim et al.*, 2008], which is evident from 1997 to 2006 in SeaWiFS images as well (Fig. 4.16). This is consistent with the increasing PC1 over both of these time periods, which indicates shoaling of isopycnals, and increasing nutrient amounts in the upper-ocean (Fig. 4.15). Thus the density PC1 appears to be a viable proxy for primary production during the years when nitrate and chlorophyll were not measured in CalCOFI.

4.4 Summary and conclusion

Upper-ocean nitrate concentration has been measured regularly in CalCOFI since 1984, but its variability in earlier decades, since 1949, is not well known. In order to reconstruct nitrate variability in the earlier decades of CalCOFI, and thereby link it to observed biological changes, an analysis of the relation between nitrate and density was performed.

Vertical sections of density from 10-100m depth in CalCOFI have similar characteristics to nitrate sections on seasonal timescales, and they are both mainly driven by seasonal wind stress in the southern California Current (SCC). The leading principal components (PC's) of density (39%) and nitrate (36%) seasonal anomalies for the sections measured from 1984-2006 are coherent. A combined empirical orthogonal function (EOF) analysis of density and nitrate anomalies reveals that isopycnals shoal and the upper-ocean nutrient content increases from the early 1990's to 2006 at low frequency, which is consistent with the observed macrozooplankton displacement volume biomass increase after the early 1990's.

Since the 1st PC of upper-ocean density is correlated with the upper-ocean nitrate content, density can be used as a quantitative proxy for nitrate in earlier decades of CalCOFI. The nitrate proxy provides a new perspective on the bottom-up forcing of the long-term changes in macrozooplankton observed in CalCOFI. PC1 of the 10m-100m density anomalies from the 56-year CalCOFI sections explains 36% of the variance, which is comparable to the variance explained in the shorter 1984-2006 time period and serves as the nitrate proxy. The nitrate proxy PC1 decreases from 1950 to the early 1990's, but increases afterwards, which is a similar tendency that the macrozooplankton displacement volume biomass time series exhibits, supporting the idea that bottom-up forcing by the physical climate system drives the changes in the zooplankton.

The nitrate proxy PC1 has a significant correlation with the Pacific Decadal Oscillation (PDO) index, although not with the North Pacific Gyre Oscillation (NPGO) index, indicating that the forcing is not local to CalCOFI but associated with basin-scale climate processes.

4.5 Acknowledgments

We gratefully acknowledge funding from NSF through the California Current Ecosystem LTER (OCE-0417616), NOAA through IOOS and ECPC (NA17RJ1231), NASA through MAP (NNG06GC98G), DOE through CCPP (DE-FG02-04ER63857), and ONR through PO (N00014-05-1-0363).

.

Appendix: Numerical modeling

Surface intensified warming and strengthened stratification have been observed in the CC [*Roemmich and McGowan*, 1995; *McGowan et al.*, 1998; *Kim and Miller*, 2007] To investigate how surface warming affects coastal circulation and nutrient supply, two numerical model runs with different surface heat-flux forcing (**SST0** and **SST1**) were conducted with the same initial conditions and wind stress forcing using ROMS (Regional Ocean Modeling System). These model experiments were forced by monthly climatology of COADS wind stress, surface heat fluxes determined by a relaxation to Levitus monthly-mean climatological SST, and Levitus ocean boundary conditions (including radiation) following *Marchesiello et al.* [2003], after a 5-year spin-up. **SST1** ("warmed ocean") was derived from **SST0** ("regular ocean" with relaxation to Levitus SST) by adding 1^{o}C to the monthly-mean Levitus SST field of **SST0**. In each case, the model was run for 10 years and then ensemble averaged to compute a seasonal cycle and to reduce the noise from the mesoscale eddies, which contribute to the lateral and vertical mixing processes.

These runs included a passive tracer, meant to represent NO_3 in the CalCOFI region. NO3 is initialized from the WOD seasonal climatology, and specified at the model boundaries, and thus represents a deep ocean reservoir of nutrient that enters the photic zone by advection and mixing as the model run evolves. This numerical modeling study with ROMS has been used to show how nutrient flux driven by surface wind stress is affected by an altered surface heat flux forcing. Two boxes in the CC from the surface to 200 m were taken as control volumes (Fig. 4.17, box I and box II) and NO_3 mass flux was calculated (Fig. 4.18). The mass flux is positive in the upwelling season (spring –

early summer), but the magnitude of the mass flux in the central CC is larger than that in the SCB (Fig. 4.18). The model data show the spatial gradient of surface nutrient concentration, which is consistent with the 1st EOF mode of SeaWiFS chlorophyll, and higher nutrient flux in the central CC than in the SCB, which is consistent with the 2nd EOF mode (Fig. 4.16).

The 1°C warmed SST forcing did not drive a simple increase or decrease in nutrient mass flux over the seasonal cycle (Fig. 4.18ab). During some times of the year, the fluxes increase but in other times, they decrease. The surface area average of NO_3 concentration in box I and II (north and south of Pt Conception) showed similar responses in each box in both cases, but they did not change consistently between the two cases. (Fig. 4.18cd). In the central CC (box I), the *regular ocean* (SST0) tended to exhibit a larger amount of surface NO_3, and presumably primary production, than the *warmed ocean* (SST1). Since this model does not include any biological activity, nitrate brought by mid-depth ocean transport or bottom boundary layer transport accumulate more effectively in the upper ocean in case SST0.

The central CC (box I) is a well-known upwelling-driven ecosystem [*Abbott and Barksdale*, 1991; *Legaard and Thomas*, 2006]. In the high chlorophyll coastal band, it has been suggested that cross-shelf transport in the mid-depth ocean (with lower nutrient concentration than the bottom boundary layer) becomes more important than bottom boundary layer transport (which brings higher nutrient concentration water to the euphotic zone) when the upper-ocean stratification (buoyancy frequency) strengthens and vertical turbulence decreases [*Lentz and Chapman*, 2004; *Doney*, 2006]. This appears to explain the decrease of surface averaged nitrate in the central CC (box I) for the SST1 simulation. However, this simple explanation does not seem to apply in the SCB (box II) where coastal upwelling is much weaker than in the other region of the CC north of Pt Conception [*Strub et al.*, 1990; *Pickett and Paduan*, 2003; *Legaard and Thomas*, 2006]. Thermocline lifting by the Ekman transport is also weak in the SCB, so that the depth and curvature of the thermocline in the warmer SST case in the coastal ocean is not significantly different than the regular SST case, which is consistent with the results found by *Kim and Miller* [2007] in the CalCOFI observations.

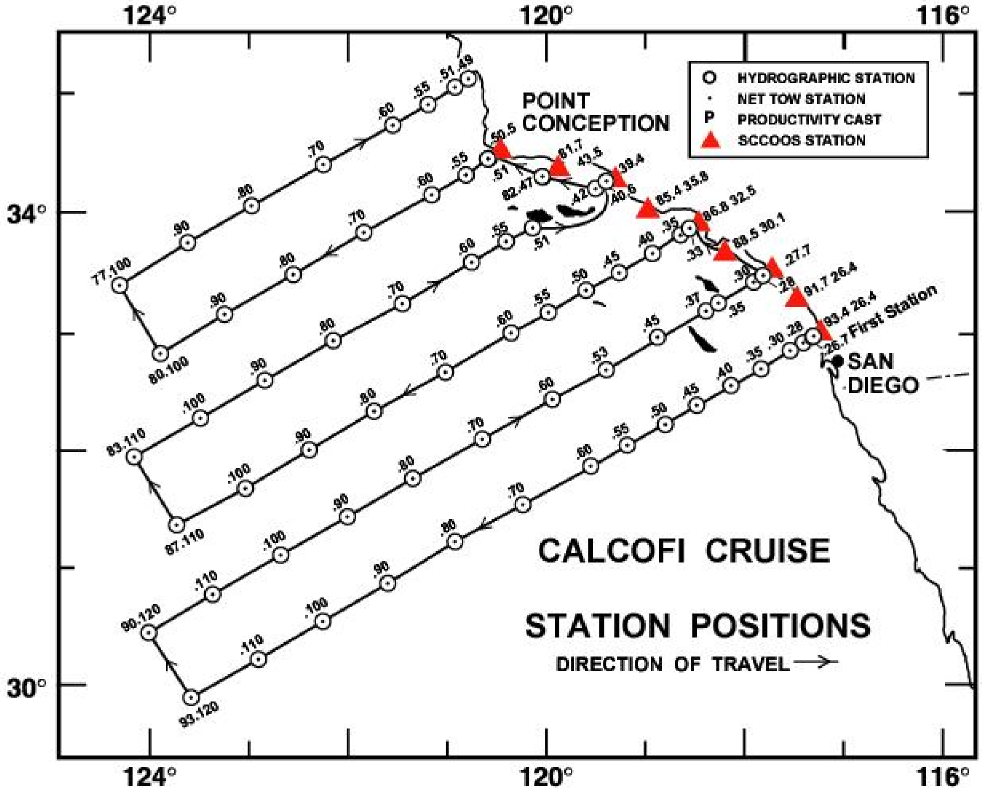


Fig 4.1. CalCOFI measurements have been regularly made at the 66 nominal stations of this map.

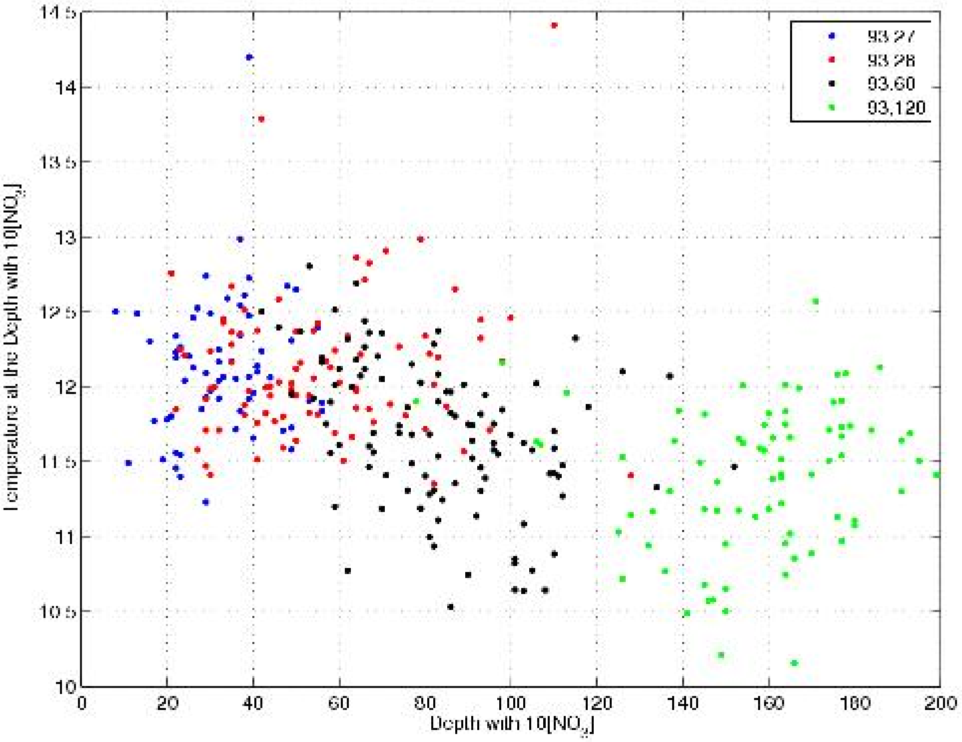


Fig 4.2. Water depth with nitrate concentration of 10 μM/L (D_{10NO3}) versus temperature at the D_{10NO3} (T_{10NO3}). D_{NO3} and T_{10NO3} have insignificant correlation. Colors represent different CalCOFI stations of Line 93. Coastal stations have shallower D_{10NO3} than offshore stations.

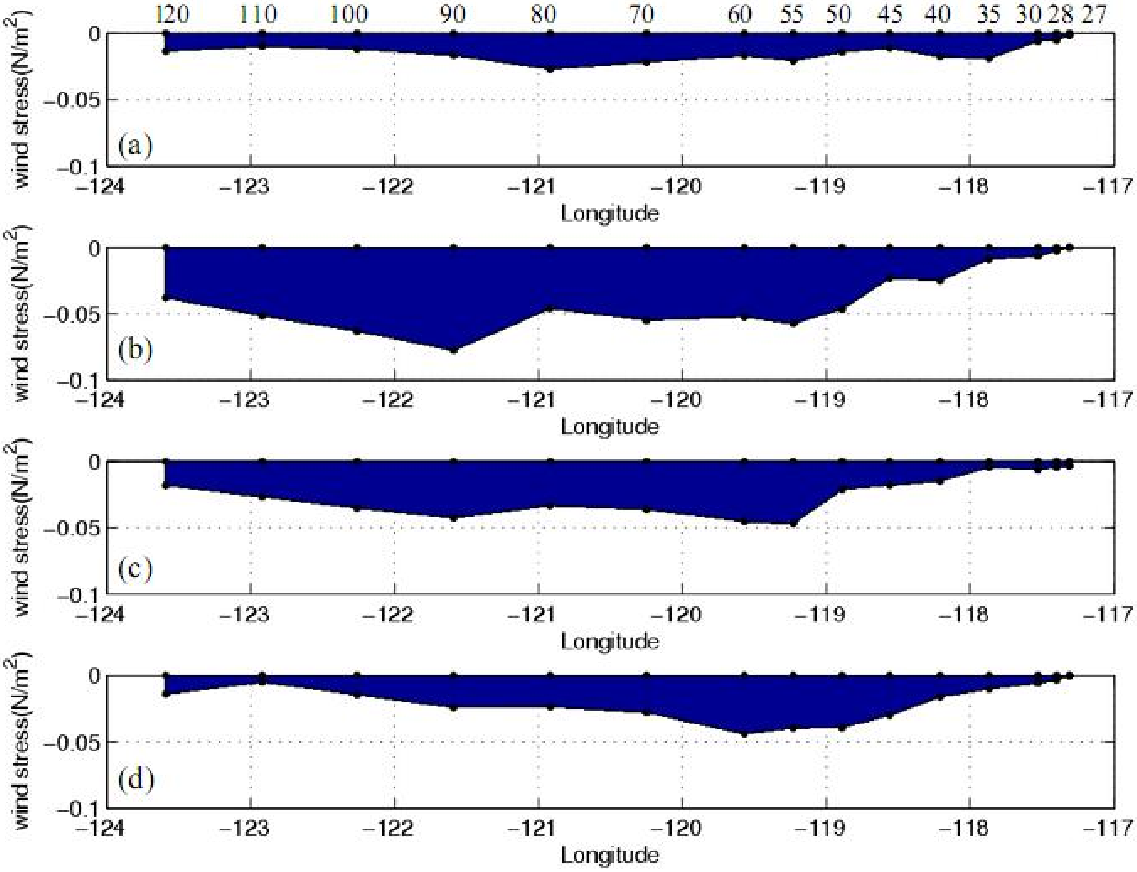


Fig 4.3. Seasonal alongshore wind stress along Line 93 using CalCOFI data. Winter (a), spring (b), summer (c), and fall (d) are Jan. – Mar., Apr. – Jun., Jul. – Sep., and Oct. – Dec. averages, respectively. Station numbers are marked on the top axis. Alongshore axis is perpendicular to Line 93.

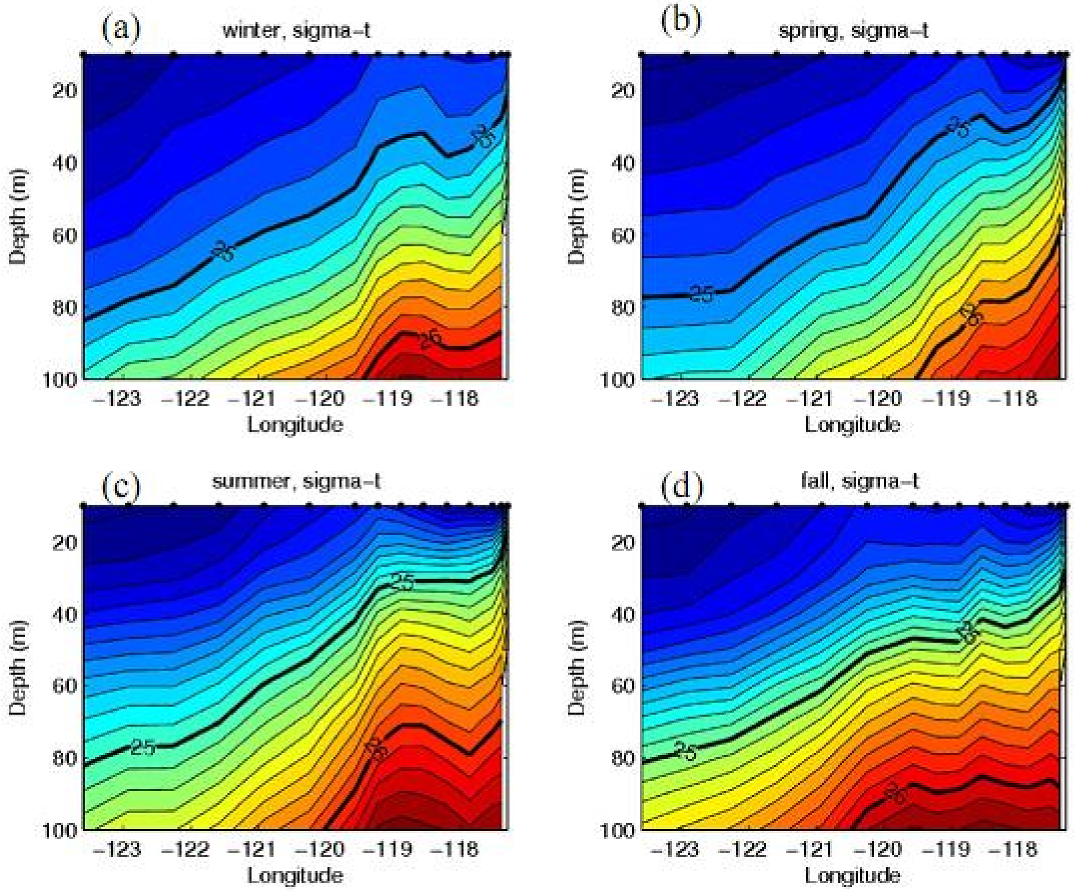


Fig. 4.4. Seasonal averages of sigma-t along Line 93 from 1985 to 2006. Black dots along the top axis for each figure represent CalCOFI stations of Line93. Thick black lines are 25 and 26 sigma-t isopycnals.

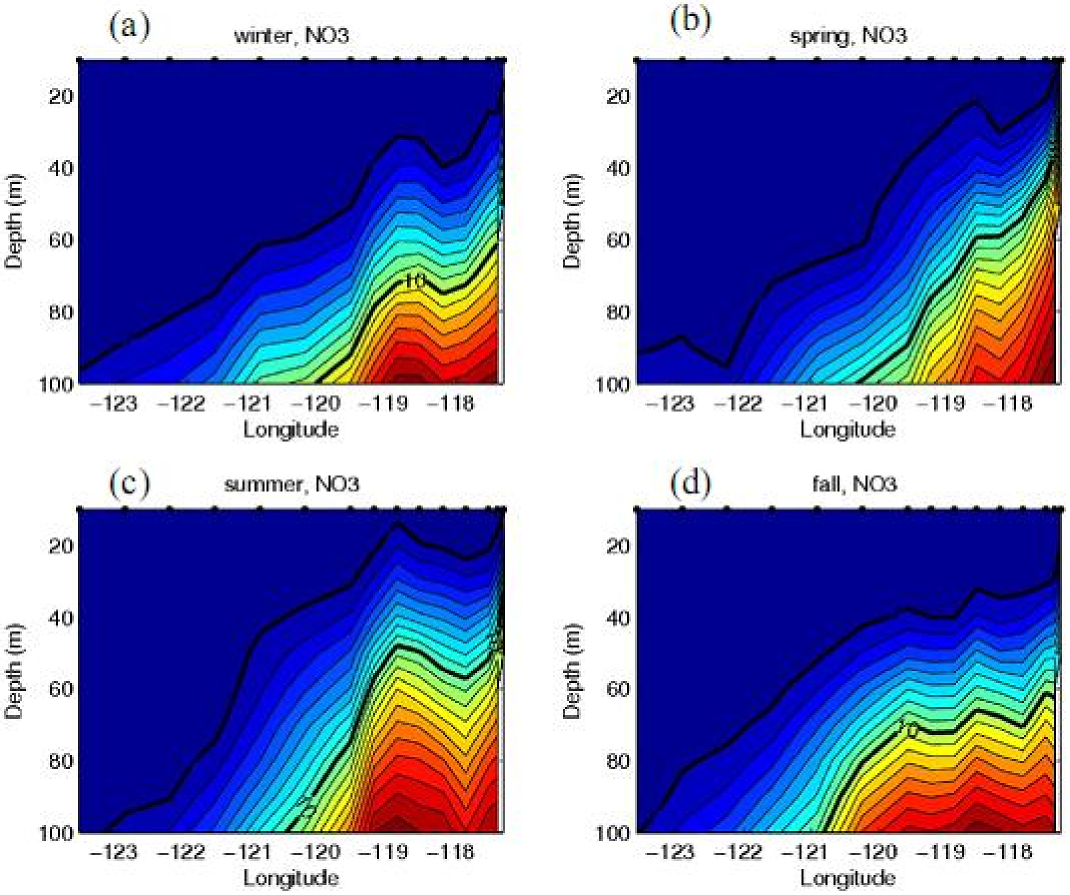


Fig. 4.5. Same as Figure 4.2, but for nitrate. Thick black lines are 1 and 10 μM/L.

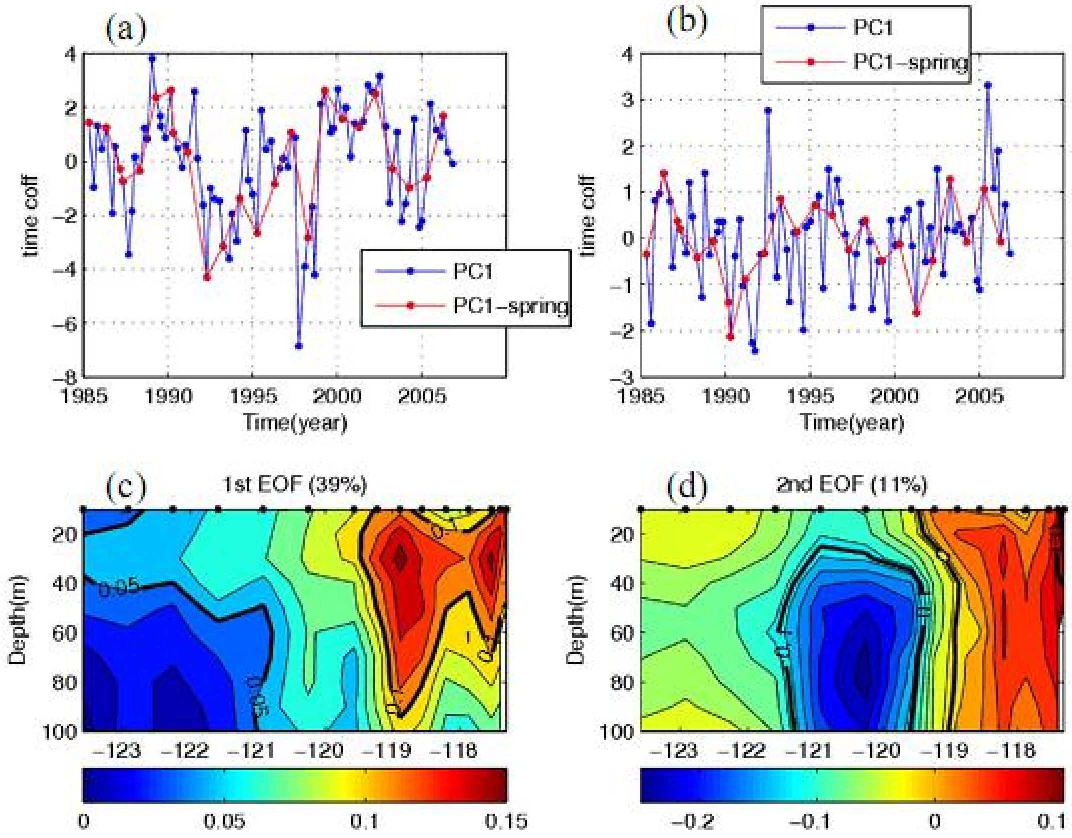


Fig. 4.6. Principal components (a, b) and depth-longitude sections of eigenvectors (c, d) for the 1st and 2nd EOFs calculated with matrix M1 (seasonal density anomalies of Line 93). Spring cruises are marked as red dots (a, b). Black dots along top axis of (c) and (d) represent CalCOFI stations of Line 93. The 1st and 2nd EOF modes account for 39% and 11% of total variance, respectively.

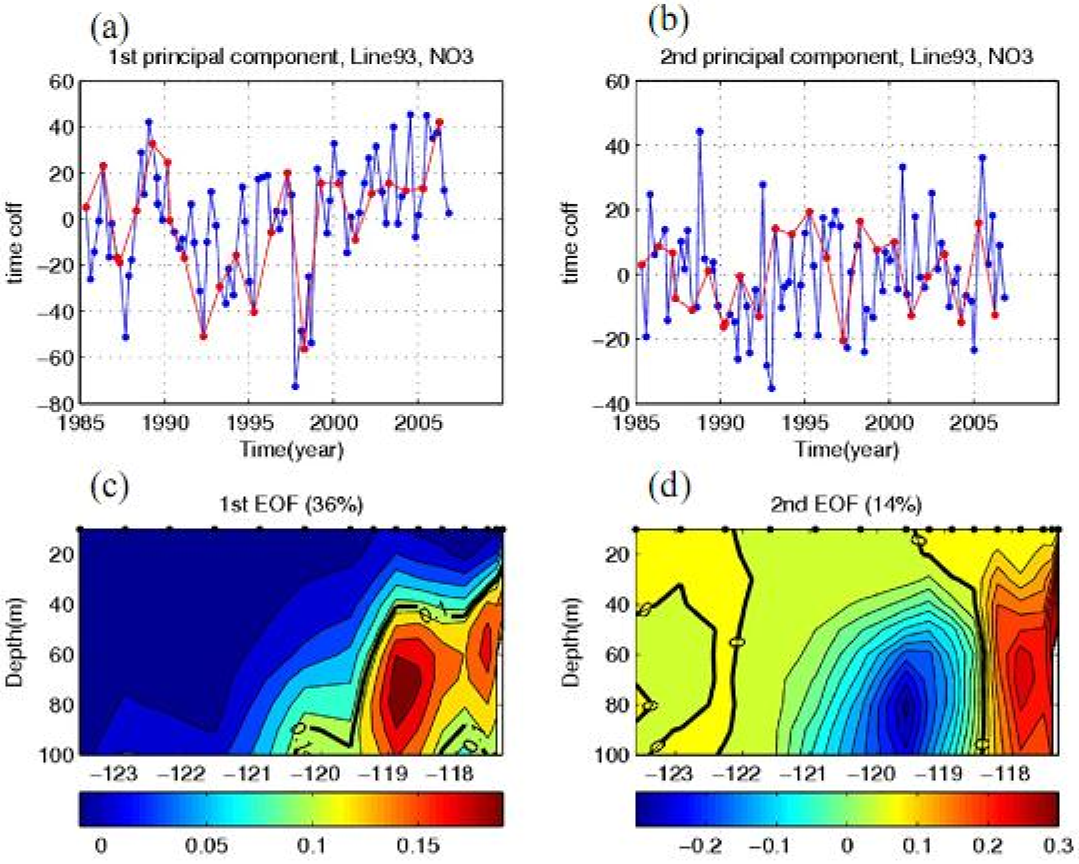


Fig. 4.7. Same as Fig. 1.6 but calculated with matrix M2 (seasonal nitrate anomalies of Line 93). The 1st and 2nd EOF modes account for 36% and 14% of total variance, respectively.

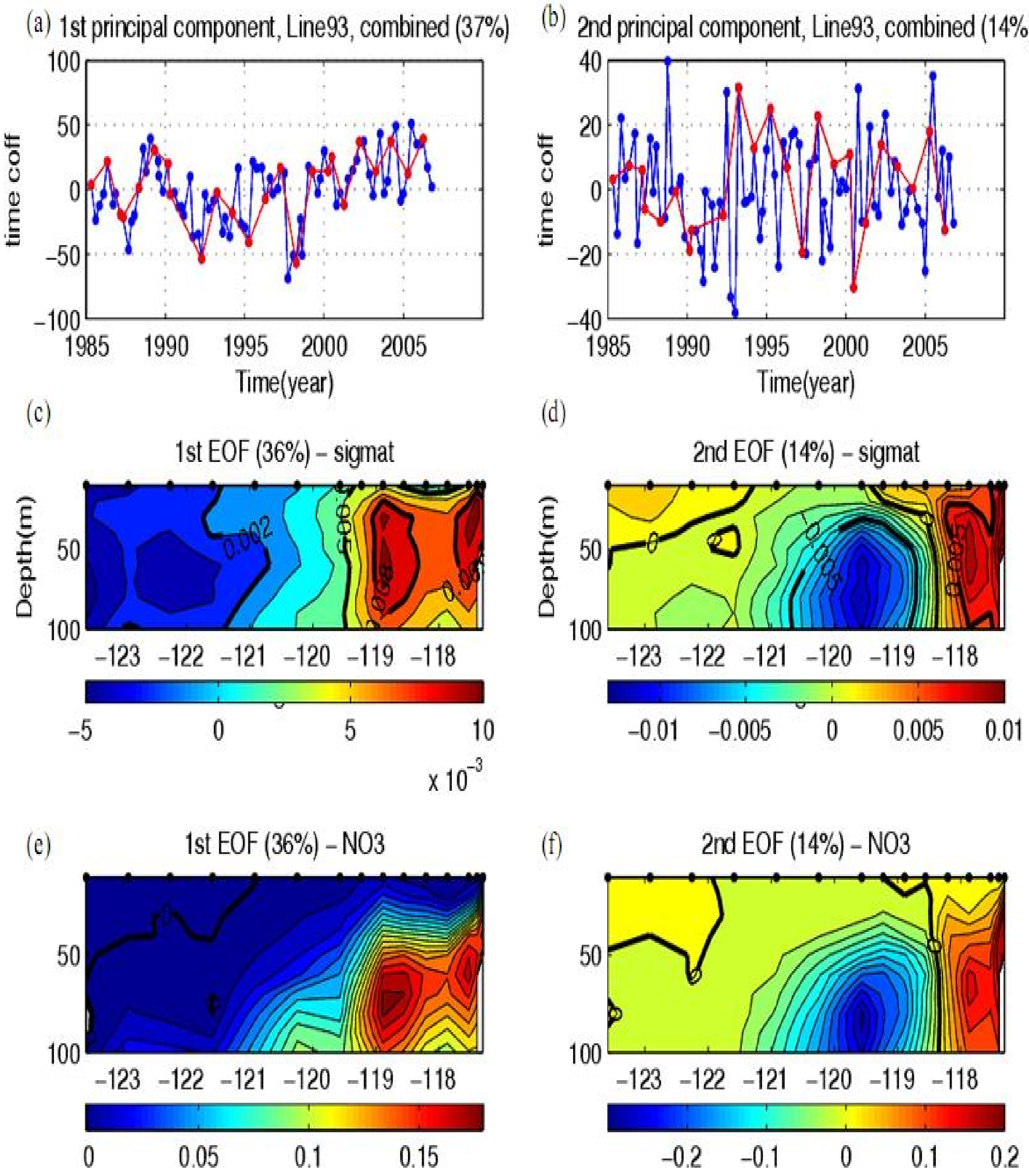


Fig. 4.8. Principal components (a, b) and depth-longitude sections of eigenvectors (c – f) for combined matrix of M1 and M2. The 1st and 2nd EOF modes account for 36% and 14% of total variance, respectively. The leading principal component (a) increases from the early 1990's. Red dots (a, b) are spring cruises.

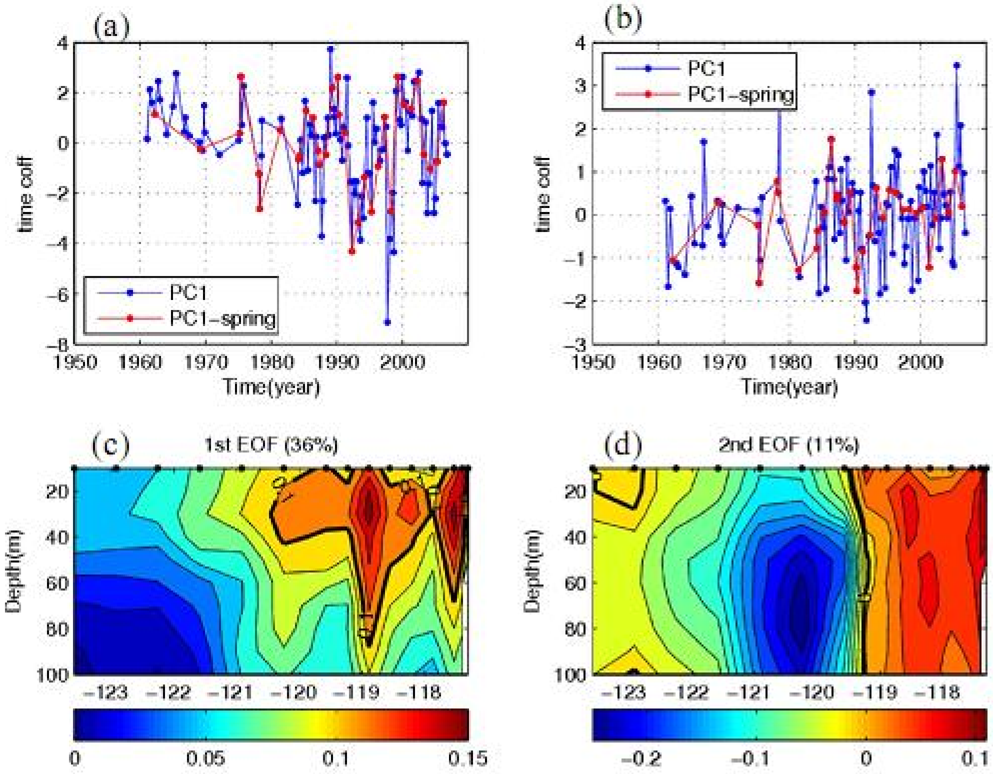


Fig. 4.9. Principal components (a, b) and depth-longitude sections of eigenvectors (c, d) for seasonal density anomalies along Line 93. Density sections of 123 CalCOFI cruises were selected for this analysis out of 331 cruises from 1950 to 2006. Selected cruises sampled both temperature and salinity profiles at more than 13 stations out of 15 stations of Line 93. The leading principal component (PC1) decreased until the early 1990's and then increased afterwards.

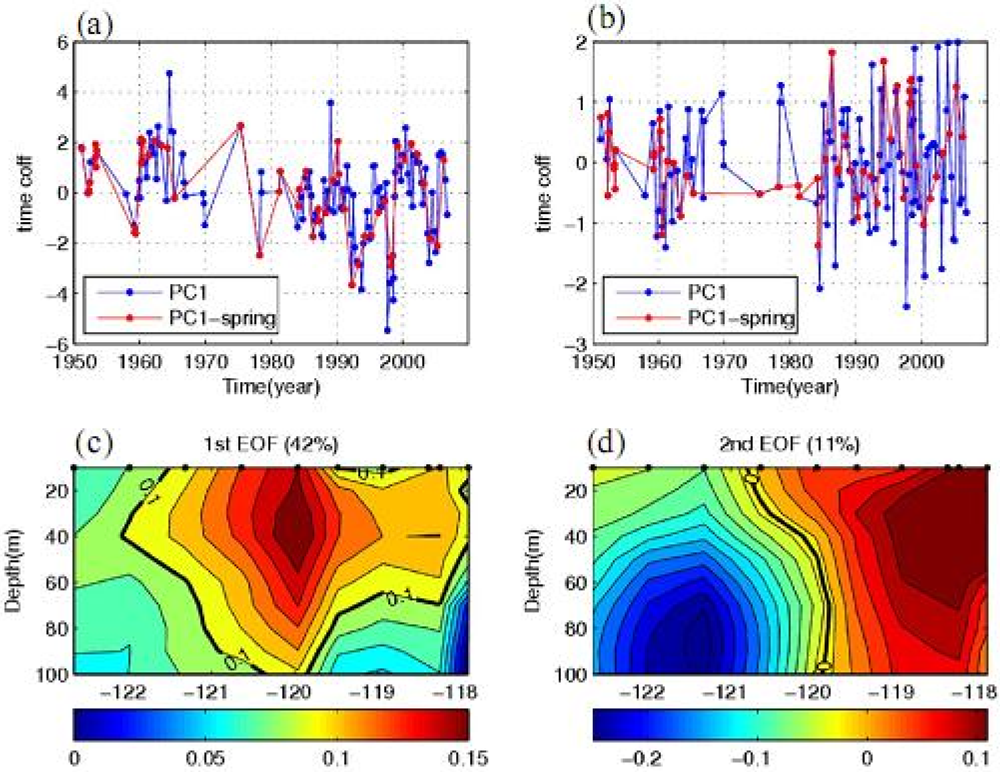


Fig. 4.10. Same as Figure 4.7 but for Line 90. 155 CalCOFI cruises were selected for this analysis out of 331 cruises from 1950 to 2006.

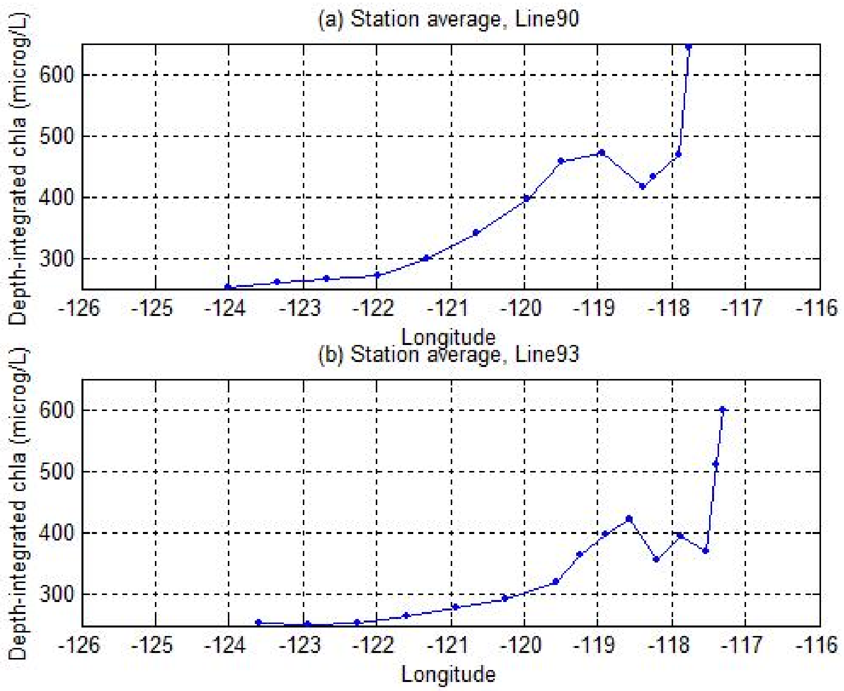


Fig. 4.11. Depth-integrated chlorophyll for each station of Line 90 (a) and Line 93 (b) for 1985-2006.

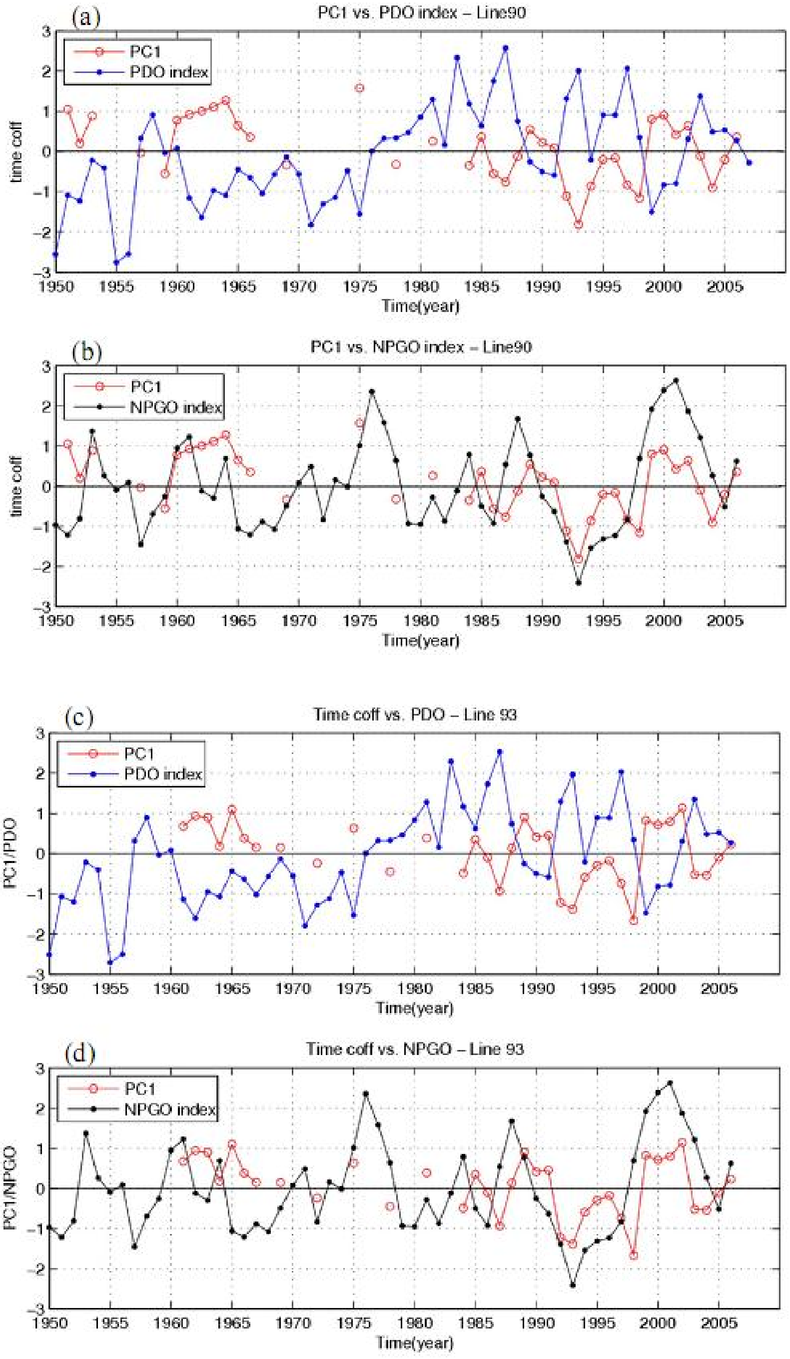


Fig. 4.12. Yearly averages of leading principle components (PC1, red dots) for Line 90 (a, b) and Line 93 (c, d) are plotted with yearly averages of PDO (blue dots, a and c) and NPGO (black dots, b and d) indices.

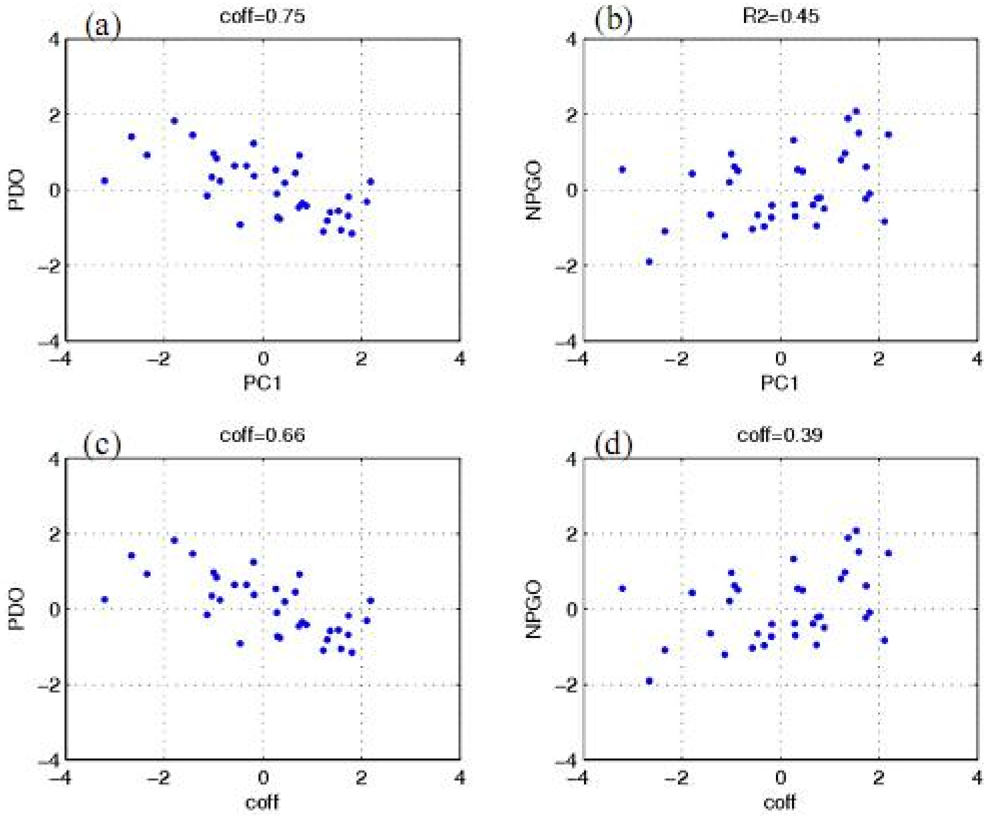


Fig. 4.13. Scatter plots of annual PC1s and two indices (PDO and NPGO) that represents basin-scale physical climate changes in Pacific. (a) and (b) are Line 90 and (c) and (d) are Line 93.

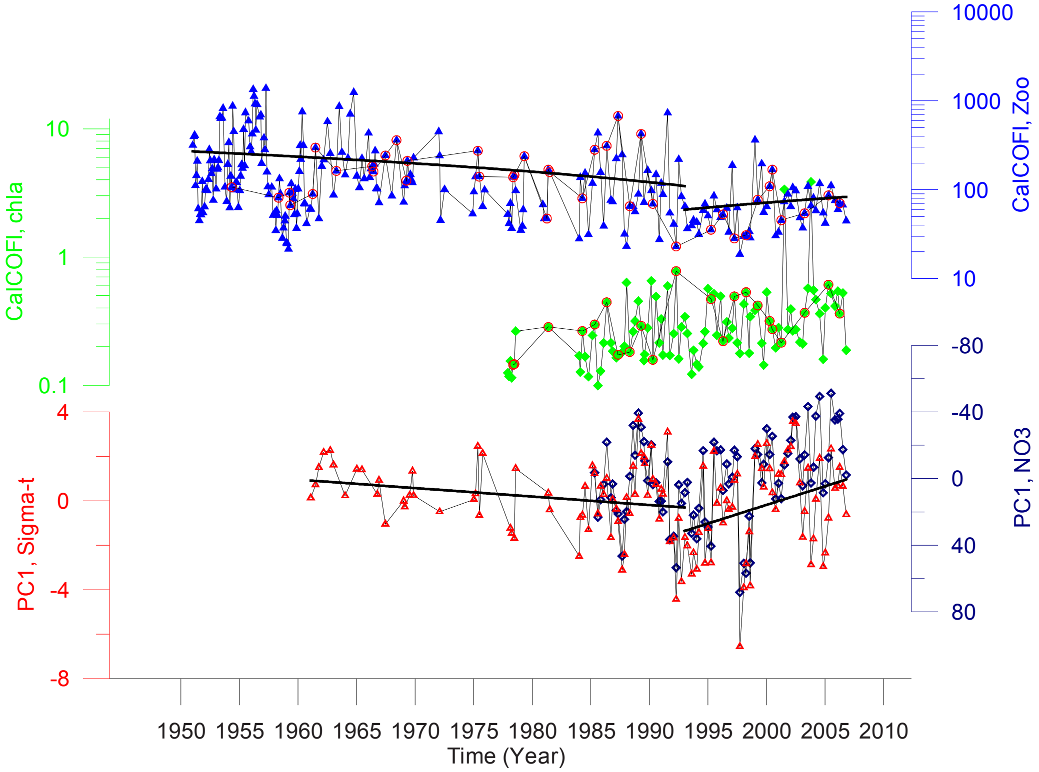


Fig. 4.14. Macrozooplankton displacement volume is averaged for each cruise along Line 93 (top panel, blue triangles). Observations in spring cruises are overlaid as red circles. Notice that macrozooplankton volume decreases from 1950's to the early 1990's, but increases afterwards.

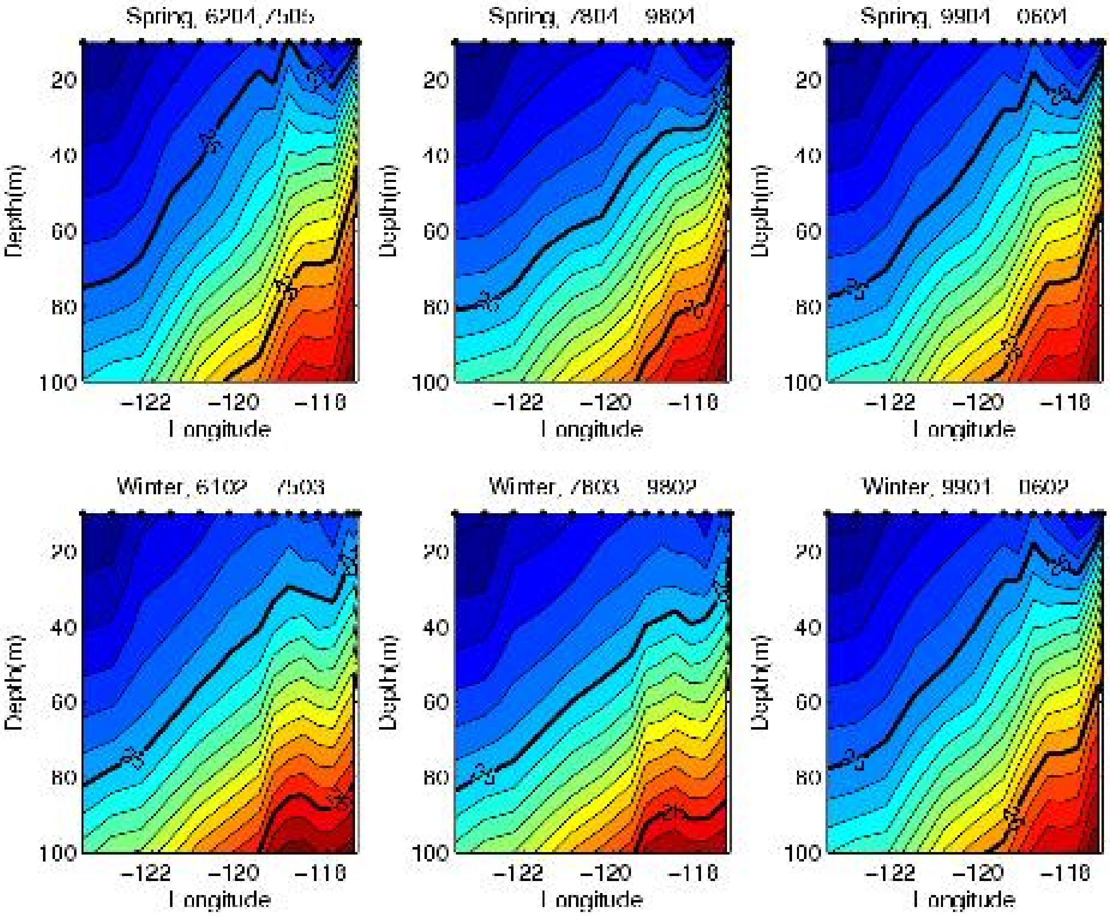


Fig. 4.15. Density sections in spring (top panels) and winter (bottom panels) along Line 93 for three epochs (1961 – 1975, 1978 – 1999, and 2000 – 2006) reconstructed from the EOF analysis with 57-year density matrix. Thick black lines are 25 and 26 sigma-t contours. Contour interval is 0.1 sigma-t.

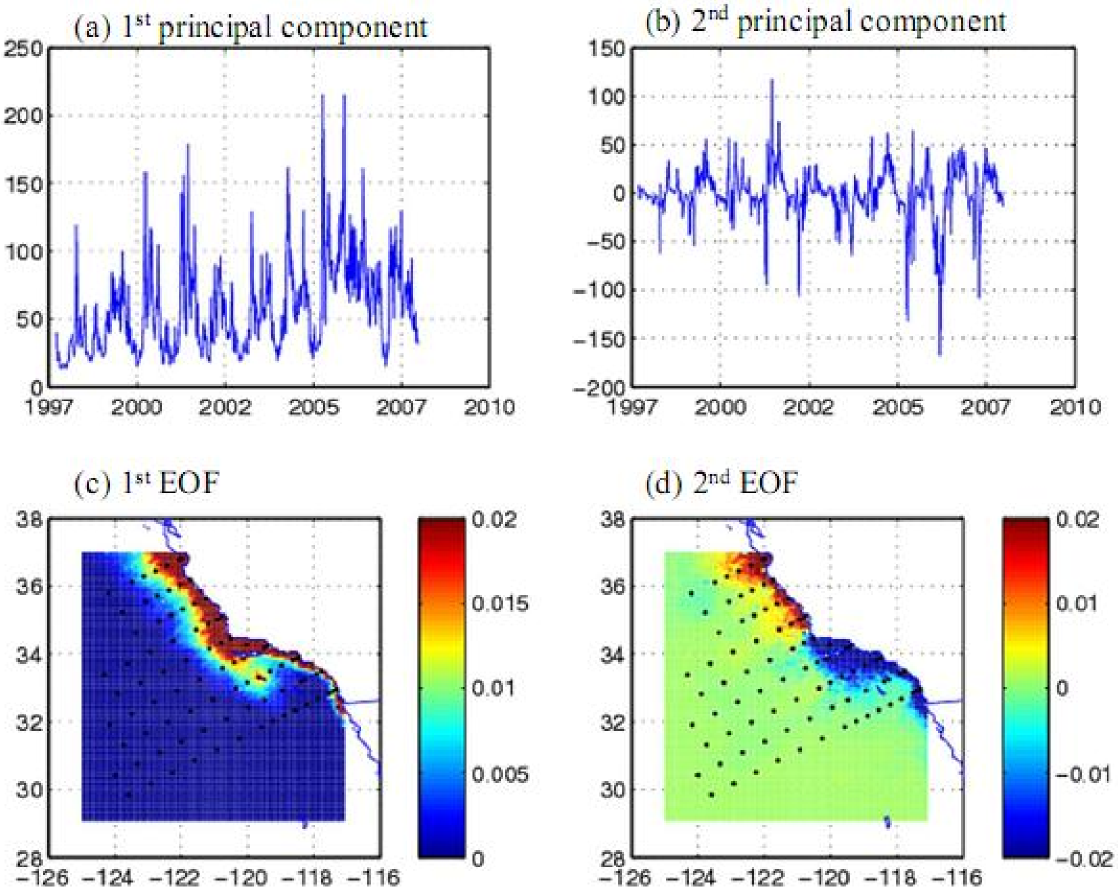


Fig. 4.16. EOF analysis of monthly surface chlorophyll derived from daily SeaWiFS images. The seasonal cycle and the spatial gradient of surface chlorophyll between high concentration coastal band and oligotrophic offshore is detected by the 1st EOF mode (c). The 2nd EOF mode shows that the California Current (CC) off the central California has higher chlorophyll concentration than the southern CC. The 1st and 2nd EOFs account for 40% and 7% of total variance.

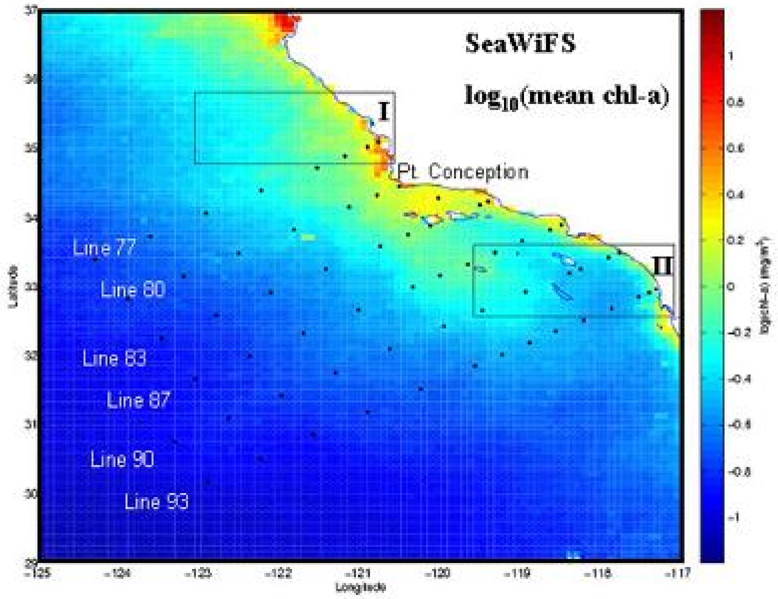


Fig. 4.17. Domain for numerical modeling study using Regional Ocean Modeling System (ROMS). Background color shading is averaged surface chlorophyll from Sep 1997 to Oct 2000. Black dots represent nominal stations of the current CalCOFI grid.

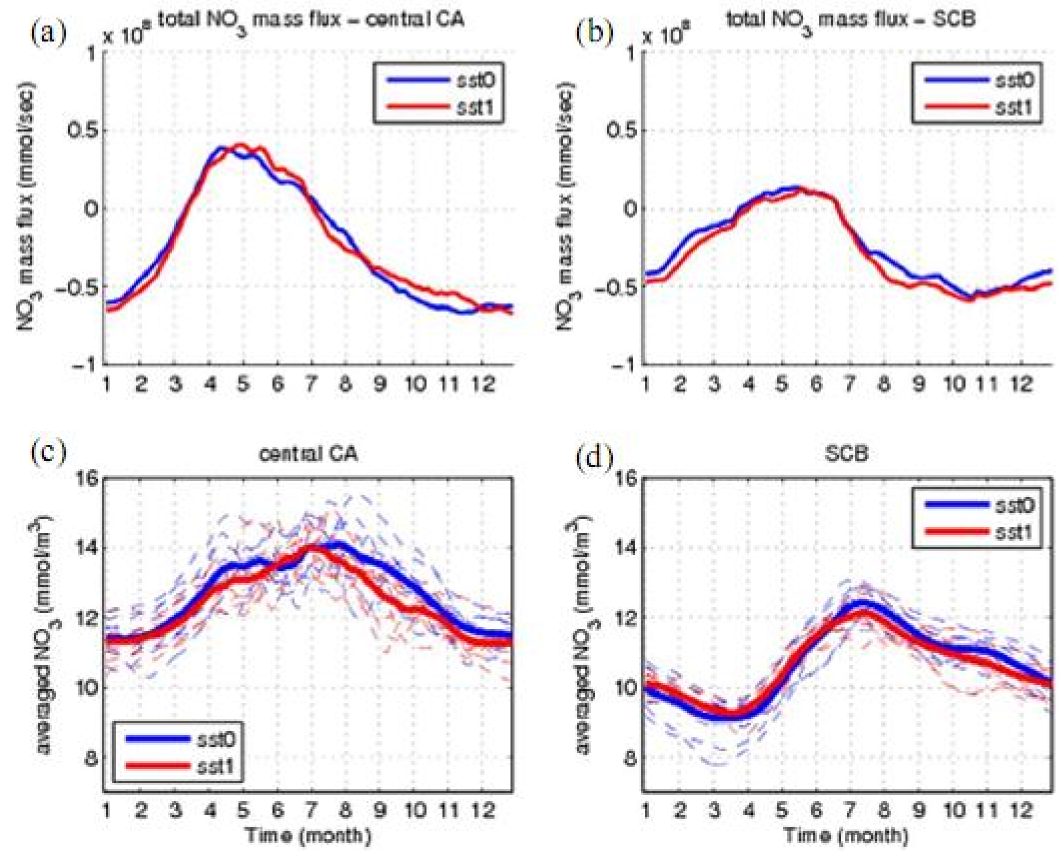


Fig. 4.18. Monthly averages of NO$_3$ mass flux in the central California ((a), box I in Figure 4.14) and SCB ((b), box II in Figure 4.14) are calculated with ROMS numerical simulation 10 year ensemble average. Positive sign means that mass is coming into the control volume. Surface NO$_3$ concentrations averaged over the area in the box I (c) and box II (d). Dotted lines are model results for each year of SST0 and SST1; thick solid lines are ensemble average of the 10 realizations.

References

Abbott, M.R., and B. Barksdale, Phytoplankton Pigment Patterns and Wind Forcing Off Central California, *Journal of Geophysical Research-Oceans*, *96* (C8), 14649-14667, 1991.

Bograd, S.J., and R.J. Lynn, Physical-biological coupling in the California Current during the 1997-99 El Niño-La Niña cycle, *Geophysical Research Letters*, *28* (2), 275-278, 2001.

Bograd, S.J., and R.J. Lynn, Long-term variability in the Southern California Current System, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2355-2370, 2003.

Di Lorenzo, E., Seasonal dynamics of the surface circulation in the Southern California Current System, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2371-2388, 2003.

Di Lorenzo, E., A.J. Miller, N. Schneider, and J.C. McWilliams, The warming of the California current system: Dynamics and ecosystem implications, *Journal of Physical Oceanography*, *35* (3), 336-362, 2005.

Di Lorenzo, E., N. Schneider, K.M.Cobb, P.J.S. Franks, K. Chhak, A.J. Miller, J.C.McWilliams, S.J.Bograd, H.Arango, E. Curchitser, T.M.Powell, and P.Riviere, North Pacific Gyre Oscillation Links Ocean Climate and Ecosystem Change, *Geophysical Research Letters*, 2008.

Doney, S.C., Oceanography - Plankton in a warmer world, *Nature*, *444* (7120), 695-696, 2006.

Hayward, T.L., and E.L. Venrick, Nearsurface pattern in the California Current: coupling between physical and biological structure, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *45* (8-9), 1617-1638, 1998.

Henson, S.A., and A.C. Thomas, Phytoplankton scales of variability in the California Current System: 1. Interannual and cross-shelf variability, *Journal of Geophysical Research-Oceans*, *112*, doi:10.1029/2006JC004039, 2007.

Kim, H.-J., and A.J. Miller, Did the Thermocline Deepen in the California Current after the 1976/77 Climate Regime Shift?, *Journal of Physical Oceanography*, *37* (6), 1733-1739, 2007.

Kim, H.-J., A.J. Miller, J. McGowan, and M. Carter, Climate and coastal algal blooms in the Southern California Bight, *Progress in Oceanography*, *sub judice*, 2008.

Lavaniegos, B.E., and M.D. Ohman, Long-term changes in pelagic tunicates of the California Current, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2473-2498, 2003.

Lavaniegos, B.E., and M.D. Ohman, Coherence of long-term variations of zooplankton in two sectors of the California Current System, *Progress in Oceanography*, *75* (1), 42-69, 2007.

Legaard, K.R., and A.C. Thomas, Spatial patterns in seasonal and interannual variability of chlorophyll and sea surface temperature in the California Current, *Journal of Geophysical Research-Oceans*, *111* (C06032), doi:10.1029/2005JC003282, 2006.

Lentz, S.J., and D.C. Chapman, The importance of Nonlinear cross-shelf momentum flux during wind-driven coastal upwelling, *Journal of Physical Oceanography*, *34* (11), 2444-2457, 2004.

Mantua, N.J., and S.R. Hare, The Pacific decadal oscillation, *Journal of Oceanography*, *58* (1), 35-44, 2002.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bulletin of the American Meteorological Society*, *78* (6), 1069-1079, 1997.

Marchesiello, P., J.C. McWilliams, and A. Shchepetkin, Equilibrium structure and dynamics of the California Current System, *Journal of Physical Oceanography*, *33* (4), 753-783, 2003.

McGowan, J.A., S.J. Bograd, R.J. Lynn, and A.J. Miller, The biological response to the 1977 regime shift in the California Current, *Deep-Sea Research Part II-Topical Studies in Oceanography*, *50* (14-16), 2567-2582, 2003.

McGowan, J.A., D.R. Cayan, and L.M. Dorman, Climate-ocean variability and ecosystem response in the northeast Pacific, *Science*, *281* (5374), 210-217, 1998.

Mestas-Nunez, A.M., and A.J. Miller, Interdecadal variability and climate change in the eastern tropical Pacific: A review, *Progress in Oceanography*, *69* (2-4), 267-284, 2006.

Pickett, M.H., and J.D. Paduan, Ekman transport and pumping in the California Current based on the U.S. Navy's high-resolution atmospheric model (COAMPS), *Journal of Geophysical Research-Oceans*, *108* (C10), 2003.

Roemmich, D., and J. McGowan, Climatic Warming and the Decline of Zooplankton in the California Current, *Science*, *267* (5202), 1324-1326, 1995.

Rykaczewski, R.R., and D.M. Checkley, Jr, Influence of ocean winds on the pelagic ecosystem in upwelling regions, 10.1073/pnas.0711777105, *Proceedings of the National Academy of Sciences*, *105* (6), 1965-1970, 2008.

Schneider, N., and B.D. Cornuelle, The forcing of the Pacific decadal oscillation, *Journal of Climate*, *18* (21), 4355-4373, 2005.

Strub, P.T., C. James, A.C. Thomas, and M.R. Abbott, Seasonal and Nonseasonal Variability of Satellite-Derived Surface Pigment Concentration in the California Current, *Journal of Geophysical Research-Oceans*, *95* (C7), 11501-11530, 1990.

Winant, C.D., and C.E. Dorman, Seasonal patterns of surface wind stress and heat flux over the Southern California Bight, *Journal of Geophysical Research-Oceans*, *102* (C3), 5641-5653, 1997.