



Coastal phytoplankton blooms in the Southern California Bight

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ABSTRACT

Surface chlorophyll (CHL) measured at the Scripps Pier in the Southern California Bight (SCB) for 18 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 1990s, the spring bloom occurred earlier in the year and with larger amplitudes compared to those of the 1980s. Seasonal anomalies of the Pier CHL have no significant correlation with local winds, local SST, or upwelling index, which implies that classical coastal upwelling is not directly responsible for driving chlorophyll variations in nearshore SCB.

The annual mean Pier CHL exhibits an increasing trend, whereas the Pier SST has no evident concomitant trend during the CHL observation period. The interannual variation of the Pier CHL is not correlated with tropical El Niño or La Niña conditions over the entire observing period. However, the Pier CHL was significantly influenced by El Niño/Southern Oscillation during the 1997/1998 El Niño and 1998/1999 La Niña transition period. The Pier CHL is highly coherent at long periods (3–7 years) with nearby offshore *in situ* surface CHL at the CalCOFI (California Cooperative Fisheries Investigations) station 93.27.

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1. Introduction

Coastal algal blooms have been reported in the Southern California Bight (SCB) for over 100 years (Torrey, 1902). Beginning around 1918, W.E. Allen began a 20-year program of monitoring phytoplankton populations by daily counts of cell numbers from water samples taken at the end of the Scripps Pier (32° 52.0'N, 117° 15.4'W, Fig. 1) (Allen, 1938, 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 interannual 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.

High primary production in coastal waters in the SCB is seasonal and has an inshore–offshore gradient. Sverdrup and Allen (1939) noted this spatial gradient by counting the number of diatoms per liter in the SCB. They showed that recently upwelled “new” inshore surface water contains many diatoms whereas “old” offshore water has few diatoms.

Since the pioneering research of Sverdrup and Allen (1939), physical and biochemical variables have been measured to better understand the link between physical processes and biological responses in the SCB. For instance, the California Cooperative Fisher-

ies Investigations (CalCOFI) program has conducted routine measurements of chlorophyll and major nutrients, in addition to hydrographic surveys, since 1984 (Hayward and Venrick, 1998). However, very nearshore waters adjacent to the coastline were not regularly observed until Southern California Coastal Ocean Observing System (SCCOOS) stations were added to the current CalCOFI grid in 2004. Therefore the magnitude and variability of primary productivity in nearshore waters of the SCB is not yet well known.

Remote sensing data of surface chlorophyll also show the contrast of productive coastal water and oligotrophic offshore water in the California Current (Strub et al., 1990; Eppley, 1992; Thomas et al., 1994; Legaard and Thomas, 2006). However, satellite chlorophyll data from very nearshore waters have systematic and random errors due to the optical complexity of nearshore water caused by organic and inorganic suspended particles and bottom reflectance (Kahru and Mitchell, 1999; Darecki and Stramski, 2004). The discrepancy between SeaWiFS satellite chlorophyll and water-sampled chlorophyll at the Pier is larger than that between SeaWiFS chlorophyll and CalCOFI shipboard chlorophyll measurement in offshore water (Kim, 2008). Thus the satellite-derived chlorophyll has not been suitable for study of chlorophyll variability over the inner shelf close to the coastline in the SCB.

Surface chlorophyll was measured at the end of Scripps Pier twice a week from 1983 to 2000. This 18-year time series is a rare long-term ecosystem monitoring record that provides an unprecedented view of the variability and nature of coastal phytoplankton blooms in the nearshore SCB. Surface chlorophyll in the

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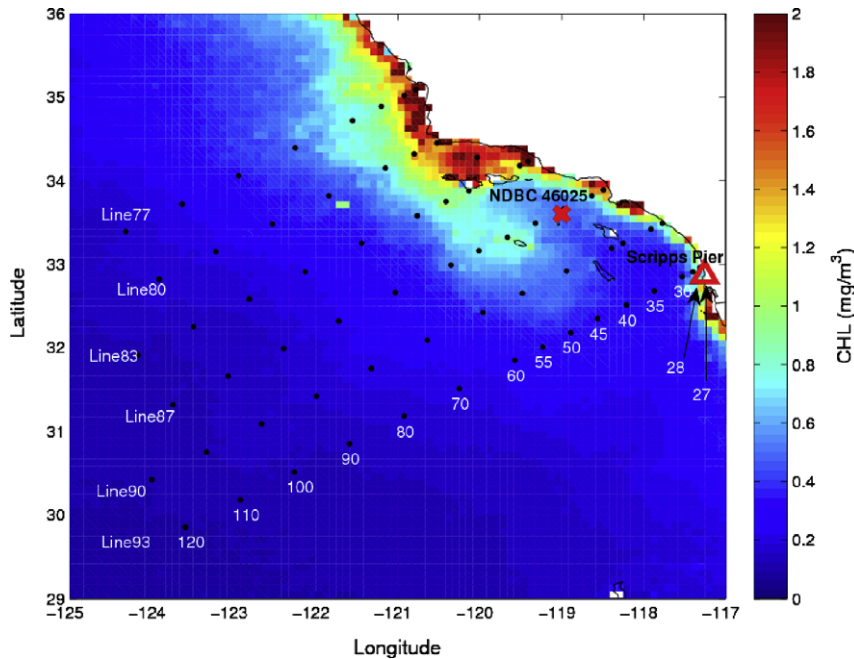


Fig. 1. The locations of the Scripps Pier (triangle), NDBC buoy 46025 (cross), and current CalCOFI stations (black dots) with nominal CalCOFI line and station numbers are shown. Background color map is annual climatological mean surface chlorophyll observed by SeaWiFS (1997–2000), which clearly shows the spatial gradient of productive coastal water and oligotrophic offshore water.)

southern California Current is significantly correlated with depth-integrated chlorophyll and depth-integrated primary production (Hayward and Venrick, 1982; Mantyla et al., 1995; Millan-Nunez et al., 1996). In this paper, we will characterize the seasonal cycle, interannual variability and long-term trends of surface phytoplankton bloom events using the Scripps Pier time series and CalCOFI dataset. We will then examine the Pier chlorophyll variability with respect to both local and remote physical oceanographic variability.

2. Data and methods

Two independent data sets of surface chlorophyll (CHL) were used to analyze spatial and temporal variability: the Scripps Pier time series and CalCOFI ship-based measurements. We focused on the Scripps Pier time series to understand seasonal, interannual, and long-term variations of surface CHL in the nearshore, and to examine the spatial connection between the Scripps Pier and nearby CalCOFI stations. Additionally, several physical time series described below were utilized to attempt to explain various aspects of the CHL observations.

2.1. Scripps Pier time series

Scripps Pier is located at the coastline (Fig. 1) and is roughly 330 m long. Surface CHL, sea surface temperature (SST), sea surface salinity (SSS), cloud cover, and wind magnitude were measured at Scripps Pier from February 17, 1983 to October 1, 2000. CHL measurements stopped in 2000, but resumed in 2005. Sampling frequency for CHL was twice per week. Target days in a week were Monday (16%) or Tuesday (31%) for the first sample and Thursday (14%) or Friday (33%) for the second sample; the remaining samples (6%) were on other days of the week. Most of time replicate samples were taken with a 30-min interval on same day. The majority of samples (96%) were taken between 7 am and 10 am. Samples were filtered through Whatman GF/F filters, extracted in 90% acetone for 24 h in the dark under refrigeration, and then read

on a Turner Designs, benchtop fluorometer (Venrick and Hayward, 1984). Note that SST and SSS have been measured *daily* at the Scripps Pier since 1916 (<http://shorestation.ucsd.edu>).

The Pier CHL time series was subsampled at the same times as quarterly CalCOFI cruises from 1984 to 2000. Time series with uniform sampling rates for coherence analysis were then obtained by linearly interpolating each time series to January, April, July, and October, which are the months that CalCOFI cruises were sampled most frequently.

2.2. Bloom characteristics

Different quantitative definitions of phytoplankton blooms have been used in previous studies. For instance, Henson and Thomas (2007) and Siegel et al. (2002) chose 5% above annual median values of surface chlorophyll to define initiation times of blooms. On the other hand, Kim et al. (2007) considered spring and fall maxima of weekly averaged surface chlorophyll time series as spring and fall blooms without defining any quantitative threshold. In this study, two different approaches are applied to characterize phytoplankton blooms. One is a constant threshold defined as a two standard deviations above the long-term average of the 18-year time series. The other is a varying threshold depending on each year's median values, which is aimed at understanding the timing and intensity of blooms on annual timescales.

2.2.1. Constant threshold: major and minor bloom

Two standard deviations (s.d. = 7.7 mg/m^3) added to the 18-year average (2.5 mg/m^3) of the Pier CHL raw data yielded a threshold value of 17.9 mg/m^3 for a *major bloom*. In order to define minor blooms, we remove the all data identified as major blooms and re-computed the average (1.9 mg/m^3) and standard deviation (1.9 mg/m^3). Two standard deviations added to the mean of the raw data without major blooms yielded a threshold value of 5.7 mg/m^3 for a *minor bloom*. This is a long-term approach which is focused on understanding changes in phytoplankton biomass over the entire 18-year time series.

2.2.2. Varying threshold

Interannual variability of the Scripps Pier CHL time series is high. When the constant threshold is applied, blooms smaller than the threshold are ignored. To better understand the temporal evolution of CHL variability in those years with weak blooms, we defined bloom initiation and termination features based on the persistence and strength of bloom events that occur each year.

The semiweekly Pier CHL time series is first interpolated to obtain 1 day temporal resolution. If CHL magnitudes rise 40% above the annual median value of that year and last at least 7 days, the first day is chosen as the bloom initiation date of each year. The termination date of the bloom is when the CHL concentration drops below the varying threshold. Bloom intensity is then defined as the averaged CHL magnitude over each bloom period.

2.2.3. CalCOFI time series

The CalCOFI program started hydrographic surveys and macrozooplankton biomass measurements in 1949 to investigate the collapse of the sardine population in the CCS (<http://calcofi.org>). CalCOFI cruises have irregular temporal sampling. They were monthly or bimonthly in the 1950s and 1960s, but quarterly cruises have been conducted since 1984. Note that there is a significant gap in 1970s.

Biological and chemical water column properties have been measured since 1984 including CHL and major nutrients over the current CalCOFI grid of 66 nominal stations (Fig. 1). The protocols for measuring CHL for the CalCOFI datasets are the same as those used for the Pier CHL measurements. Spatial resolution is roughly 70 km, but inshore stations range from 10 to 15 km apart in the cross-shelf direction. Surface CHL time series at each station from 1984 to 2000 are linearly interpolated by quarter (target months are January, April, July, and October) to obtain evenly sampled time series for coherence estimates.

2.3. NDBC buoy

Offshore SST and wind measured at station 46025 (33° 44'20"N, 119° 3'20"W, water depth = 882 m; Fig. 1) of the National Data Buoy Center (NDBC) are used to calculate linear correlation with the Pier time series. This correlation analysis is performed to examine whether the offshore wind and SST is responsible for the Pier SST and CHL variability. This buoy station is approximately 200 km away from the Scripps Pier.

2.4. Climate indices

To attempt to explain the Scripps Pier CHL variability, climate indices, as well as local physical variables (sea surface temperature, sea surface salinity, and wind magnitude) measured at the Pier, are used for linear correlation analysis. The 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 downloaded from the website (<http://www.cgd.ucar.edu>). If the Niño 3.4 index is larger (smaller) than 0.4 °C (–0.4 °C) for longer than 6 months, it is defined as an El Niño (La Niña) event (Trenberth, 1997).

The upwelling index (Bakun, 1973) indicates nutrient input from the bottom boundary layer caused by Ekman transport (Ekman, 1905). The linear correlation coefficient between the daily upwelling index at 33 °N and Pier SST/CHL is calculated (Table 1).

Pacific Decadal Oscillation (PDO, <http://jisao.washington.edu/pdo/>) and North Pacific Gyre Oscillation (NPGO, <http://www.o3d.org/npgo/>) indices are used to examine the correlation of the Pier time series with large-scale, low frequency physical variability in the Northeast Pacific. PDO is the first mode of empirical orthogonal function of North Pacific SST, which has been shown to be correlated with other physical variables and some biological changes

(Mantua et al., 1997). NPGO is the second mode of sea surface height in North Pacific, which has been shown to be correlated with biogeochemical variability of salinity, nutrients, and chlorophyll (Di Lorenzo et al., 2008).

3. Results

The Scripps Pier chlorophyll (CHL) exhibits nonlinear pulse-like signals of high frequency, large amplitude phytoplankton blooms (Fig. 2). The CHL time series also exhibits a long-term trend towards higher values in more recent years. We next quantify these basic characteristics and then relate them to physical variables and climate indices.

3.1. Long-term mean chlorophyll

The long-term (2.49 mg/m³, 1983–2000) mean CHL at the Pier is much higher than the long-term (1.15 mg/m³, 1985–2000) mean at the nearest CalCOFI station, 93.27, which is roughly 12 km northwest of the Pier and located over the shelf with water depth less than 200 m (Fig. 3). The standard deviation is also much larger at the Pier. The cross-shore structure of mean CHL from CalCOFI Line 93 reveals the inshore–offshore spatial gradient consistent with previous studies (Strub et al., 1990; Eppley, 1992; Legaard and Thomas, 2006). Higher values of CHL coincide with shallower depths, with lowest values far off the shelf in deep water (Fig. 3), similar to that observed remotely with SeaWiFS (Fig. 1).

3.2. Seasonality and the spring bloom

The monthly climatology of the Pier SST from 1983 to 2000 has a minimum in winter and maximum in summer (Fig. 4). The monthly climatology of Pier CHL has a maximum in April, which indicates the climatological spring bloom. The spring bloom occurs right after the three coldest months of the SST climatology (December, January, February) after which relatively high CHL persists through May as the SST warms (Fig. 4). The SST in each month is warmer in the 1990s (Period 2, 1990–2000) than the 1980s (Period 1, 1983–1989) by 0.84 °C in January and 0.33 °C in August, and the CHL also increases in Period 2 (Fig. 4). Note that the CHL maximum, corresponding to the climatological spring bloom, occurs in May during Period 1, whereas it happens in March with larger magnitude during Period 2 (Fig. 4). The month of the SST maximum, in contrast, does not change between these two periods.

The structure of the seasonal cycle of CHL in each year, however, is very different from the climatology. The timing of the spring CHL maximum in any given year does not necessarily coincide with the climatological peak and the monthly mean CHL shows a more complicated pattern than the monthly mean SST (Fig. 5). Visual inspection of each year in Fig. 5 suggests that three main types of bloom patterns occur: spring blooms, summer blooms, and spring–fall double blooms. Fig. 6 shows a detailed example of each of the three types of blooms. These bloom types do not appear to be related in any consistent way with the SST anomalies in each year.

3.3. Quantifying phytoplankton blooms

3.3.1. Constant threshold

Using the major bloom definition with a constant threshold throughout the record, only 1.3% of the samples (24 out of 1847) exceed the threshold. The magnitude of *major blooms* by this criterion ranges between 18.19 and 218.95 mg/m³. The maximum CHL concentration occurred during the red tide observed in March, 1995.

Table 1

Linear correlation coefficients calculated using monthly averaged time series of the Pier data (CHL, SST, SSS, and wind magnitude), SST and alongshore wind stress (ustress) measured at the NDBC buoy station 46025, and the Niño 3.4 (Niño), upwelling (UPI), PDO, and NPGO indices. If the p -value is <0.01 , the correlation coefficient is printed in bold. Both the Pier CHL and SST are significantly correlated with the offshore SST measured at the NDBC buoy. The Pier SSS is significantly correlated with the NPGO index.

	Pier				NDBC buoy		Climate index			
	CHL	SST	SSS	wind	SST	ustress	Niño	UPI	PDO	NPGO
<i>Pier</i>										
CHL	–	0.08	–0.12	–0.09	–0.07	–0.08	0.01	–0.10	–0.06	–0.15
SST		–	0.02	–0.01	0.77	–0.17	0.39	–0.36	0.29	–0.23
SSS			–	0.13	0.00	0.17	–0.11	0.34	–0.20	0.53
Wind				–	0.01	0.22	0.21	0.09	–0.21	0.25
<i>NDBC</i>										
SST					–	–0.09	0.35	–0.33	0.39	–0.15
Ustress						–	–0.05	0.46	0.01	0.17
<i>Index</i>										
Niño							–	–0.28	0.44	–0.35
UPI								–	–0.20	0.32
PDO									–	–0.29
NPGO										–

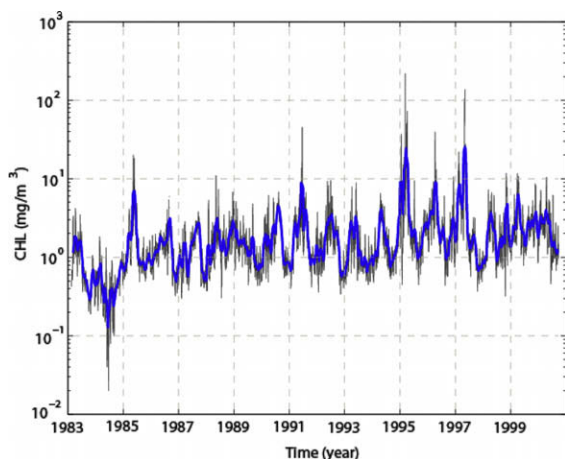


Fig. 2. Raw data of the Pier chlorophyll (thin gray line). A 5-week box-car average is used to create a smoothed time series for visualization only (thick blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The number of major and minor blooms for each month of every year and their average CHL concentrations are shown in Fig. 7. Both major (Fig. 7a and b) and minor (Fig. 7c and d) blooms tend to occur earlier and more frequently in the 1990s than in the 1980s. Averaged CHL concentration of the blooms (Fig. 7b and d) increased in recent years. Minor blooms show more complicated phenological changes. Ninety two percent of minor blooms from 1983 to 1994 occurred in Spring/Summer (April–September). But 77% of minor blooms after 1994 occurred in winter/spring (February–May). Some years in the 1980s (1983, 1984, 1987, and 1989) showed no major/minor blooms for the entire year and early phytoplankton blooms in February or March did not occur until 1995.

3.3.2. Varying threshold

The varying bloom threshold criterion allows us to examine how smaller blooms may have changed over time, without being obscured by the dominant effects of the major blooms on the constant threshold criterion. The varying threshold and averaged bloom magnitude of each year generally increases with time (Fig. 8a and b). The variability in the initiation date is large during the Pier CHL observation period, but the first spring bloom of each year tends to occur earlier in most recent years (Fig. 8d). During the first 5 years (1983–1987) of the Pier CHL time series, the first

spring bloom occurred between day-51 and day-112 of each year. But the first bloom occurred earlier, between day-17 and day-65, during the last 5 years (1996–2000).

3.4. Correlations between the Pier data and physical variables

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. Physical signatures, such as cold SST and upwelling-favorable winds, should necessarily appear if coastal upwelling controls CHL concentration at the Pier. However, the Pier CHL monthly anomaly is not significantly correlated with the Pier SST anomalies (Table 1, Fig. 9). This implies that classical coastal upwelling does not explain the occurrence of coastal blooms observed at the Scripps Pier.

Previous studies also show that the SCB has relatively weak upwelling-favorable winds compared to other regions of the California Current and the maximum wind stress axis is further away from the coastline (Winant and Dorman, 1997; Pickett and Paduan, 2003; Legaard and Thomas, 2006). Moreover, the end of the Scripps Pier is located on the “inner shelf”, which is the transition region seaward of the surf zone and landward of the midshelf (Lentz, 1995; Lentz et al., 2008), where waves, cross-shelf winds and other local processes may play more important roles in determining cross-shelf transport (Fewings et al., 2008) rather than the classical coastal upwelling.

Seasonal anomalies of physical variables, SST and SSS, measured at the Pier have significant correlation with the upwelling index and the basin-scale climate patterns, of the PDO and NPGO (Table 1). In addition, the Pier SST anomalies are correlated with the NDBC buoy SST and Niño 3.4 index (Table 1). But the Pier CHL is not well explained by any of the physical variables listed in Table 1, which suggests that the biological response to physical variation is not linear and occurs in a more complicated way.

The local SST and SSS anomalies measured daily at the Scripps Pier since 1916 show significant correlation with basin-scale climate patterns indicated by PDO ($r = 0.43$, $p < 0.0001$) and NPGO ($r = 0.34$, $p < 0.0001$), respectively, (Fig. 10). McGowan et al. (1998) also show that the Pier SST anomalies have significant correlation with a basin-scale SST pattern of the North Pacific, which resembles the PDO spatial pattern. For the shorter time period, 1983–2000, the semiweekly Pier SST and SSS are also correlated with the PDO ($r = 0.30$, $p < 0.0001$) and NPGO ($r = 0.57$, $p < 0.0001$) index, respectively. The Niño 3.4 index has significant correlation with the Pier SST (Table 1, $r = 0.39$, $p < 0.0001$), but not with CHL

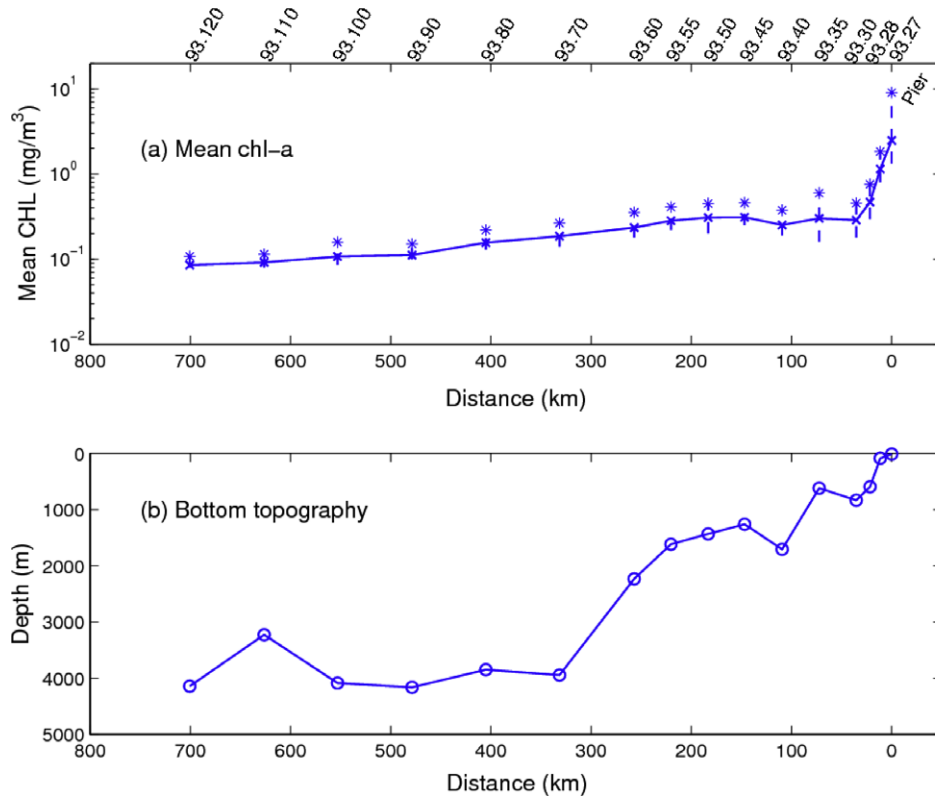


Fig. 3. (a) Median chlorophyll along CalCOFI Line 93 averaged from 1984 to 2000 for all cruises. The pier value for mean chlorophyll from 1983 to 2000 is also plotted at the coast. Star symbols indicate one standard deviation above the mean chlorophyll at each station. (b) Water depth for each station of CalCOFI Line 93. Station number is indicated at top.

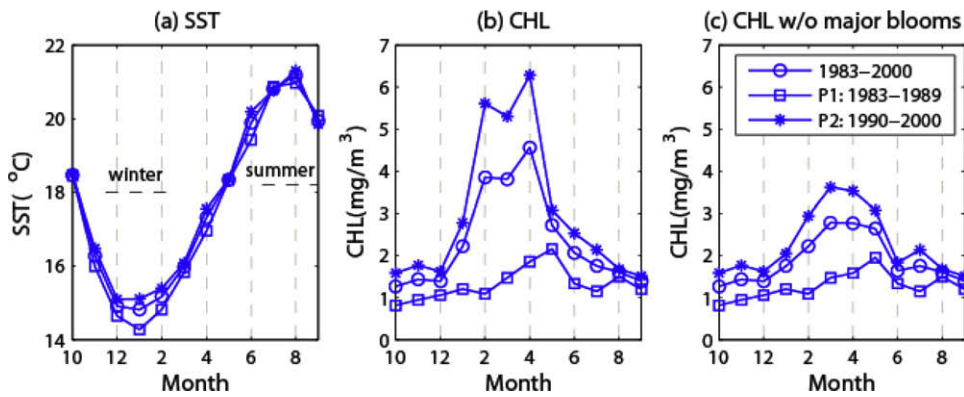


Fig. 4. Monthly climatology of (a) the Pier SST, (b) CHL, and (c) CHL without *major bloom* events for three different time periods (circle: 1983–2000; square: 1983–1989; star: 1990–2000). x-Axis starts in October.

(Table 1) over the entire 1983–2000 time series including several El Niño/Southern Oscillation (ENSO) events. This implies that remote forcing from the equator does not consistently affect biological variability in the SCB (McGowan et al., 2003; Lavaniegos and Ohman, 2007). Note, however, that both physical (SST) and biological (CHL) factors at the Pier are directly linked to the ENSO signals after the development of 1997/1998 El Niño (Fig. 11) even though the Niño 3.4 index is area-averaged SST and the Pier time series is a point measurement.

High temperature and low chlorophyll are well-known CCS characteristics of El Niños, and vice versa for La Niñas (events III, V, and D in Fig. 11), although not all of ENSO episodes show the consistent temperature and chlorophyll changes (Fig. 11). During the 1997/1998 El Niño (event V in Fig. 11), CHL anomalies were

negative, and they started to increase during the 1998/1999 La Niña (event D in Fig. 11). Since the onset of the 1997/1998 El Niño (June 1997–October 2000), correlation coefficients with the Niño 3.4 anomalies are 0.77 for the SST and -0.36 for the CHL. Details of physical and biological responses to the 1997/1998 El Niño and the 1999 La Niña in the CCS are well documented by previous studies (Bograd and Lynn, 2001; Chavez et al., 2002; Legaard and Thomas, 2006).

3.5. Long-term trend of surface chlorophyll

The time series of the Pier CHL shows an increasing tendency with time (Figs. 2 and 12). The trend is especially apparent in both the time series of annual mean anomalies and annual

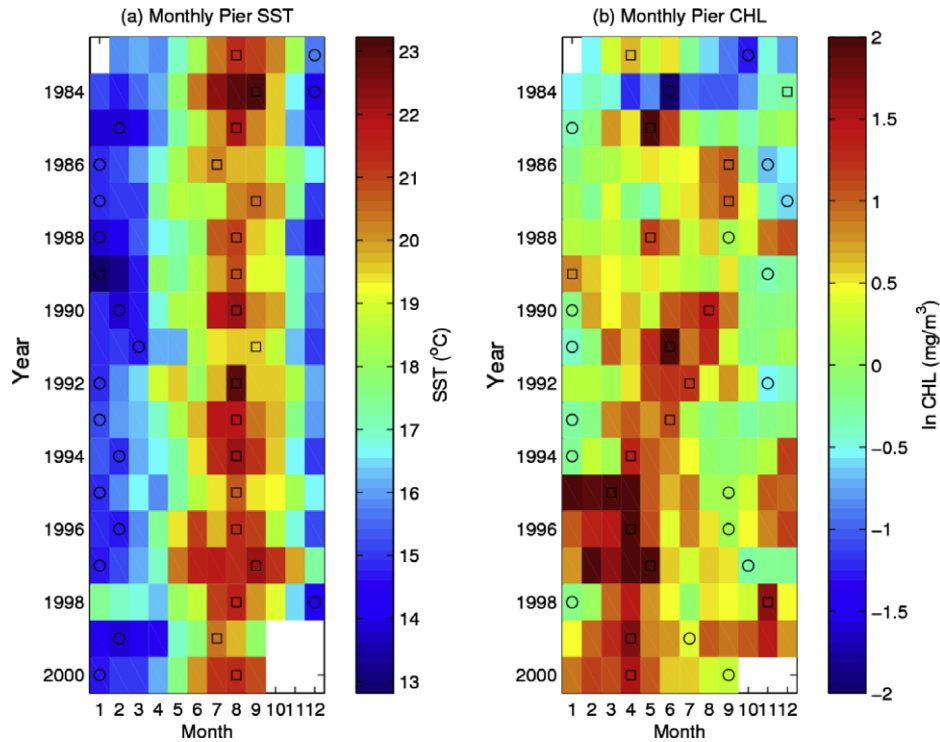


Fig. 5. Monthly means of (a) the Pier SST and (b) CHL for each year and month to indicate the seasonal cycles for each year. The SST is well explained by a seasonal cycle, but the CHL is not dominated by a seasonal cycle. Black squares are maxima and red circles are minima for each year. CHL has a minimum of 0.14 mg/m^3 and a maximum of 9.85 mg/m^3 without *major blooms* (maximum is 39.23 mg/m^3 with *major blooms*), while SST varies between 12.8 and 23.2 °C. The mean-normalized standard deviation of CHL (0.75 w/o *major blooms*, 1.65 w/*major blooms*) is much greater than that of SST (0.14).

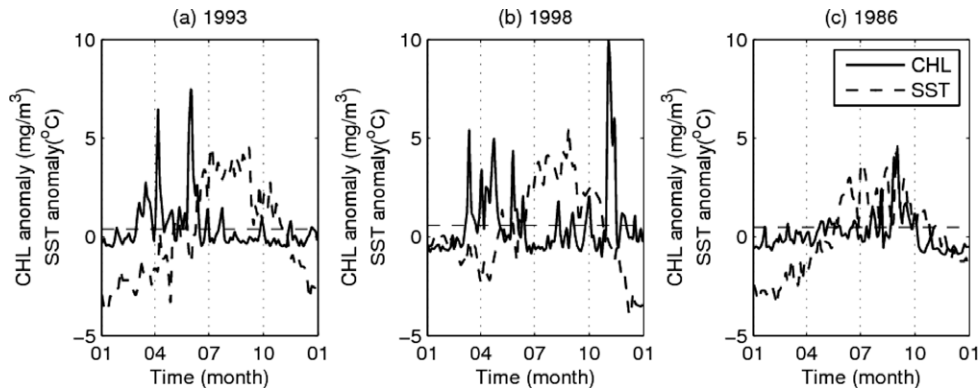


Fig. 6. Examples of (a) spring blooms, (b) spring and fall blooms, and (c) summer blooms defined by the annually varying bloom threshold described in the text, for three different years. Annual medians ((a) 18.20 , (b) 17.64 , (c) 17.73 for SST; (a) 0.97 , (b) 1.44 , (c) 1.22 for CHL) are subtracted from semiweekly raw data.

median anomalies (Fig. 12). The annual average and median of the Pier CHL monthly anomalies have a significant increasing linear trend (Fig. 12b). The slope of the Pier surface CHL linear trend is $0.158 \text{ mg/m}^3/\text{year}$ for annual mean CHL and $0.076 \text{ mg/m}^3/\text{year}$ for annual median CHL. In contrast, the Pier SST does not have a significant linear trend during the observation period, 1983–2000 (Fig. 12a). But note that the beginning of the observation period is one of the strongest El Niño years and the end of the period is a La Niña year by coincidence. These events result in large positive anomalies in 1983 and negative anomalies in 1999, which might mask an increasing linear trend. The longer-term *daily* SST time series since 1916 shows more frequent warming episodes after 1977 and a concomitant warming trend (McGowan et al., 1998).

The surface CHL variability at the Pier and CalCOFI station 93.27, 12 km away from the Pier (Fig. 1), is significantly coherent at low frequency (<0.5 cycle/year) with roughly zero phase lag (Fig. 13). These two time series, the Pier CHL and CalCOFI station 93.27 CHL, share approximately 30% of variance (squared coherence) at low frequency. Coherence at low frequency (Fig. 13) is not significant for stations further offshore from CalCOFI station of 93.27, which is located at the outer continental shelf region (water depth >500 m, Fig. 1).

4. Discussion and conclusions

Surface chlorophyll (CHL) observed at the Scripps Pier exhibits a higher mean value and larger magnitude fluctuations than CHL ob-

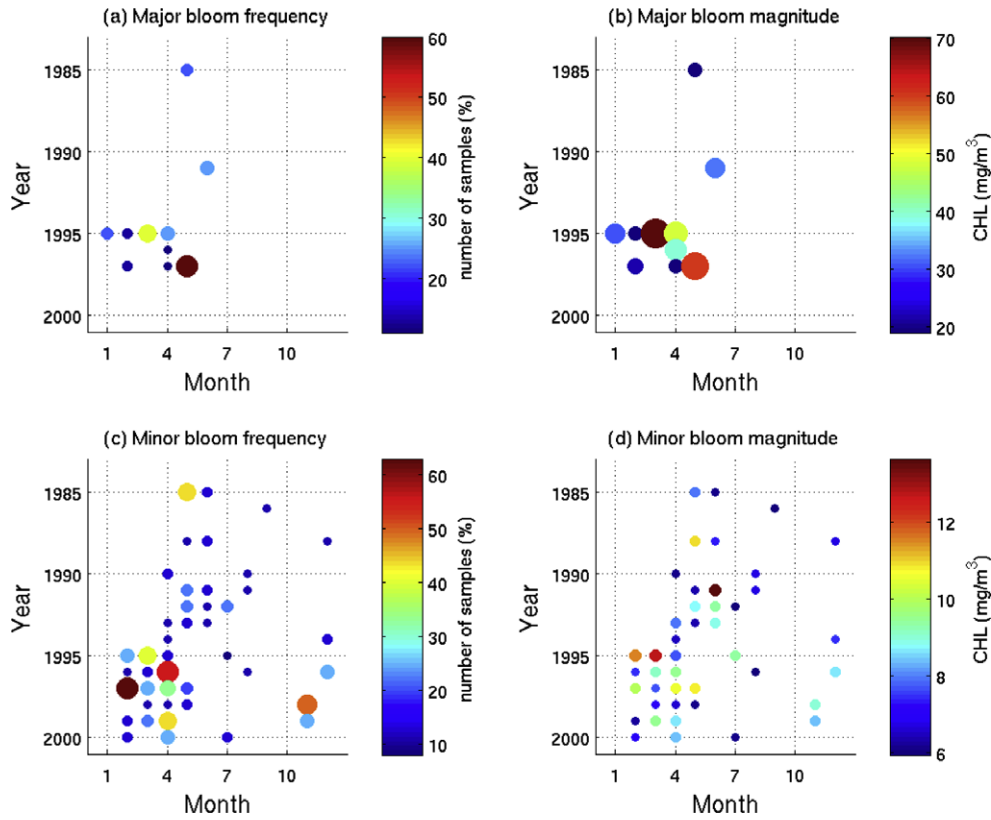


Fig. 7. Number of phytoplankton blooms (a and c) and averaged bloom magnitudes (b and d) for each month from 1983 to 2000 using the constant major/minor bloom thresholds. The size of circles is proportional to bloom frequency (a and c) and bloom magnitudes (b and d).

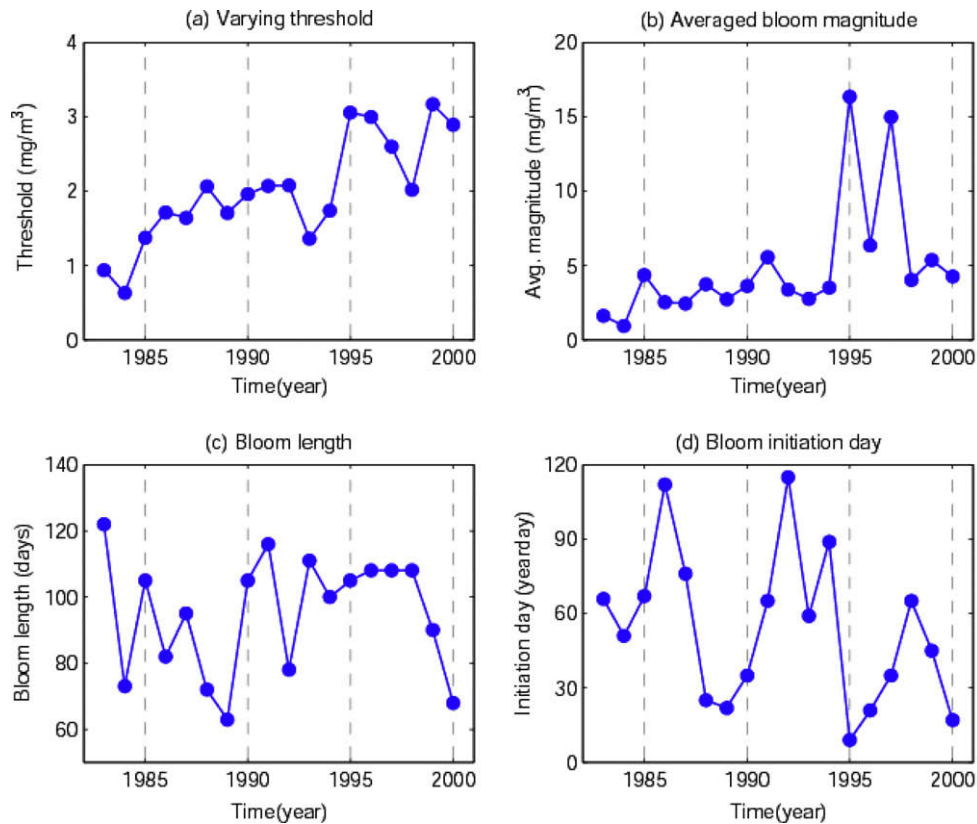


Fig. 8. (a) The annually varying bloom threshold ($1.4 \times$ median) for each year, (b) the averaged chlorophyll bloom magnitude during growing period, (c) the length of growing period, and (d) the day corresponding to the first bloom of each year (bloom initiation timing). These show that the spring bloom tends to occur earlier with larger magnitude in later years. The annual median values of the Pier chlorophyll in (a) varies between 0.45 and 2.26 mg/m³.

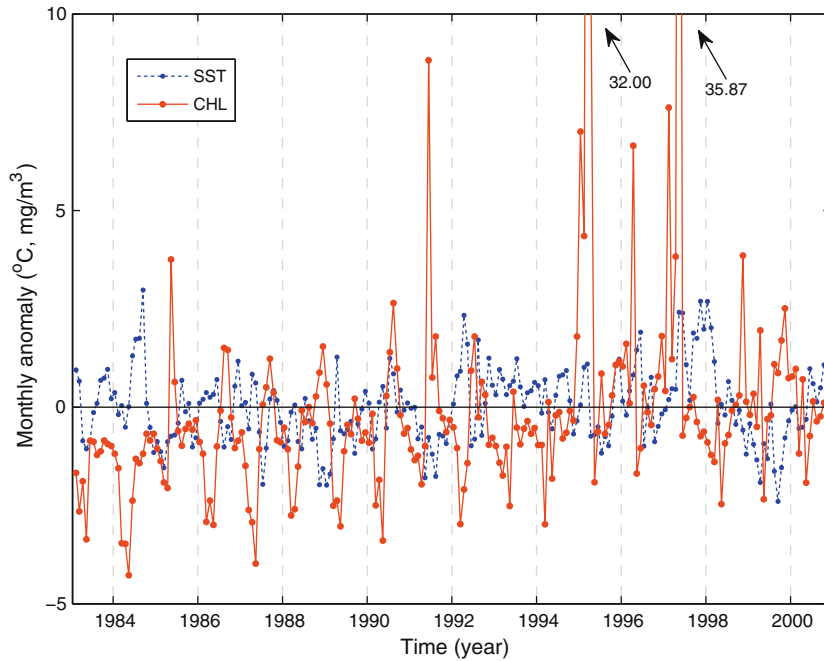


Fig. 9. Monthly anomalies of the Pier SST (dashed line) and CHL (solid line). Four points have larger magnitudes (arrows) than the y-axis range.

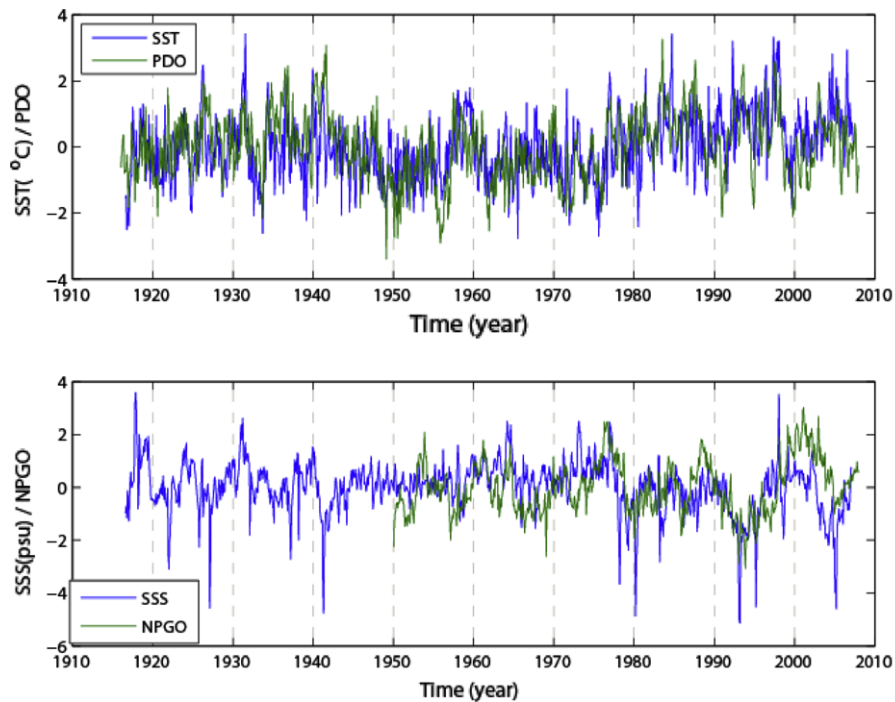


Fig. 10. The monthly-averaged *daily-sampled* Pier SST is correlated ($r = 0.43$, $p < 0.0001$) with the monthly PDO index from 1916 to 2007 (a) whereas the monthly-averaged *daily-sampled* Pier SSS is correlated ($r = 0.34$, $p < 0.0001$) with the monthly NPGO index from 1950 to 2007 (b).

served at coastal stations of CalCOFI Line 93 (Fig. 3). Major blooms, episodic occurrences of phytoplankton blooms with large magnitudes, occurred at the Pier more frequently in the 1990s than in the 1980s (Fig. 7). They are due to relatively sudden population explosions of phytoplankton and sometimes cause water discoloration. However, no evidence was found to explain the physical processes associated with these major blooms.

The seasonal cycle in Pier CHL and SST has changed in recent decades in these nearshore waters of the SCB (Fig. 4). The bloom

initiation timing (Fig. 8) and especially the maximum peak timing of each year (Fig. 5) occur earlier during the 1990s than the 1980s. Henson and Thomas (2007) show that the spring bloom starts in February in the SCB by analyzing daily SeaWiFS CHL from 1998 to 2005. This is consistent with the Pier CHL bloom initiation timing for the overlapping record, from 1998 to 2000. However, the 18-year Pier CHL observations reveal the later bloom initiation timing, occurring as late as April but varying strongly from January to April, during the preceding decades (Fig. 8d).

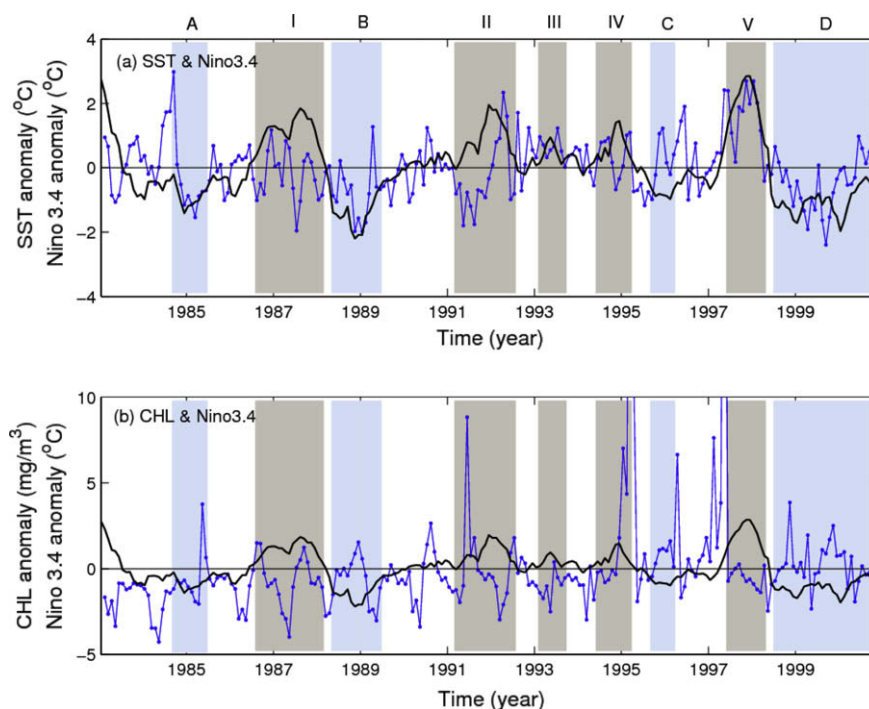


Fig. 11. Time series of Niño 3.4 monthly anomalies (black lines) and Pier SST/CHL monthly anomalies (blue lines) with respect to monthly climatology between 1983 and 2000. Five El Niño events (gray shade, roman numerals) and four La Niña events (blue shade, alphabet letters) occurred during the Pier observation period. The Pier SST anomalies are significantly correlated with Niño 3.4 index anomalies ($r = 0.39$, $p = 0.0001$), but the Pier CHL anomalies are not ($r = 0.01$, $p = 0.8985$). Note that the Pier SST ($r = 0.77$, $p < 0.0001$) and CHL ($r = -0.36$, $p = 0.0218$) were significantly influenced by the ENSO signal during the transition period from the 1997/1998 El Niño event (V) to 1998/1999 La Niña event (D).

A change in the seasonal cycle of peak surface CHL biomass has been also observed in the North Sea (Edwards and Richardson, 2004). The seasonal dinoflagellate bloom timing is highly correlated with SST, but the diatom bloom timing has no significant correlation with SST (Edwards and Richardson, 2004). Thus the phytoplankton community in the pelagic ecosystem responds to climate changes in different ways. Unfortunately, we have no species-specific time series data for this analysis to address this important issue.

Climate indices are known to be correlated with certain biological variations in the SCB for interannual timescales associated with ENSO (Reid et al., 1985; Bograd and Lynn, 2001; Legaard and Thomas, 2006) and decadal timescales associated with the PDO and NPGO (Hare and Mantua, 2000; Miller and Schneider, 2000; McGowan et al., 2003; Di Lorenzo et al., 2008). Indeed, physical variables at the Pier, SST and SSS, are significantly correlated with climate indices (Table 1, Fig. 10), which implies that even the very nearshore region might be influenced by basin-scale climate patterns. However, Pier CHL is poorly correlated with both local physical variables (the Pier SST, SSS, upwelling index) and the basin-scale climate indices (PDO, NPGO, Niño 3.4. indices), except during the strong 1997–2000 El Niño to La Niña transition. This indicates no obvious physical forcing mechanism linked to these climate patterns, except during the extreme ENSO event. Although Tont (1987), in a reanalysis of part of Allen's data, found that several species of diatoms respond to climatic fluctuations, none of the physical variables we examined show clear evidence to explain the 18 year Pier CHL variability. Thus it is still an open question how climate changes influence the biological variability in the nearshore water.

The annual mean and median surface CHL increased from 1983 to 2000 at the Pier (Fig. 12). Moreover, domain-averaged surface chlorophyll in the CalCOFI grid increased from 1978 to 2004 (Ryckaczewski and Checkley, 2008). Gregg et al. (2005) also showed

a significant increasing trend of annual averaged monthly anomalies ($0.287 \text{ mg/m}^3/\text{year}$) in SeaWiFS CHL data in the Northeastern Pacific coast (California/Mexican shelf) for 6 years from 1998 to 2003. This slope is larger than that of the Pier CHL trend ($0.158 \text{ mg/m}^3/\text{year}$) from 1983 to 2000 probably because their 6-year time series has large interannual variability. The recent study by Kahru et al. (2009) also showed increased magnitudes of chlorophyll peaks and net primary production in the California Current from 1997 to 2007 using remote sensing data.

At low frequency, the surface CHL measurements at the Pier and CalCOFI station 93.27 have high coherence (Fig. 13), which implies that nonlocal physical forcing is involved with the low frequency CHL variability. But the low frequency coherence with the Pier CHL is not significant for stations further offshore from CalCOFI station of 93.27, which is 12 km away from the Pier.

Significant coherence in the low frequency band between Pier CHL and CalCOFI station 93.27 CHL (Fig. 13) suggests that a common physical forcing might be contribute to supporting nutrient availability at the Pier and station 93.27. Cross-shelf exchange between the outer shelf and innershell water by physical forcing might influence nutrient supply to the very nearshore coastal region. Nutrient input to the nearshore might occur as a very short pulse that is not observed in the daily or semiweekly observation. For example, Cullen et al. (1982) observed nutricline shoaling preceded a dinoflagellate bloom and drastic nutrient reduction within a day 2–3 km offshore of La Jolla in 1980. To understand physical mechanisms that bring nutrients to the Pier to generate phytoplankton blooms, long-term measurements of lateral and vertical ocean transports and mixing, along with nutrient distributions and higher-frequency sampling of SST and CHL are necessary.

Nearshore patterns of phytoplankton abundance, such as those we report here, are of both economic and ecological importance. They strongly affect shoreline aesthetics and the hypoxia, which often follows bloom decay, may damage nearshore marine

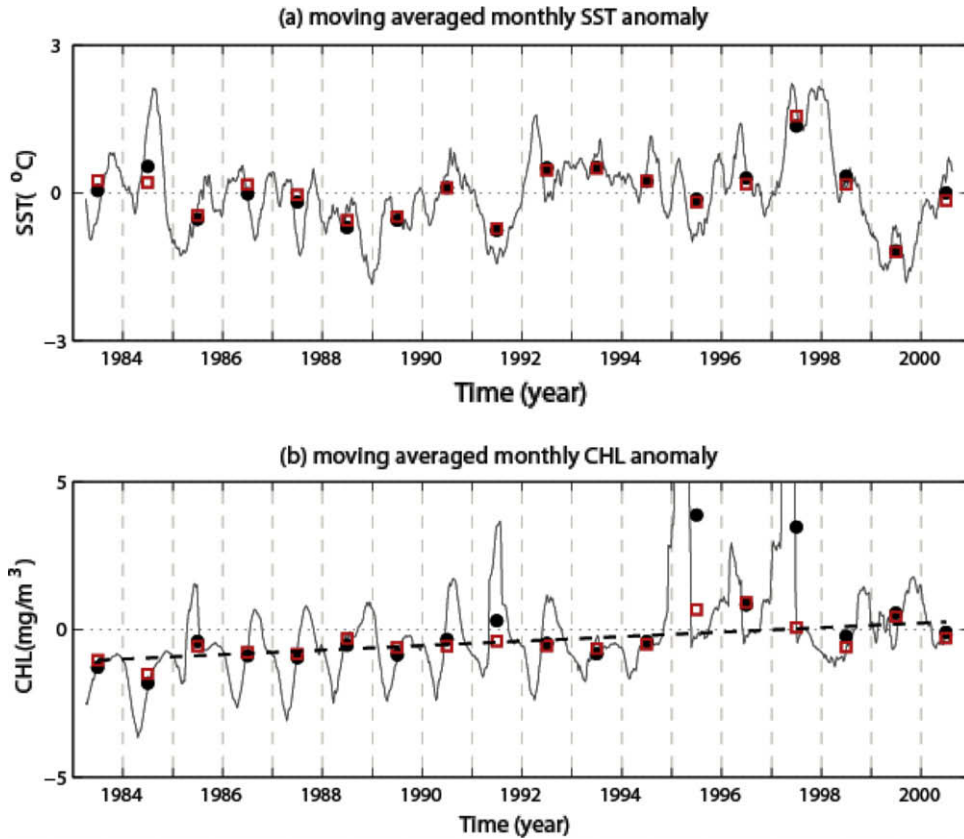


Fig. 12. Monthly seasonal anomalies of the Pier SST (a) and CHL (b) with respect to monthly climatology, smoothed by a 3 month moving average (gray lines). The Pier SST anomalies (a, gray line) exhibit an insignificant linear trend from 1983 to 2000, but the Pier CHL anomalies (b, gray line) show a significant positive linear trend ($r = 0.34$, $p < 0.0001$). The annual means (dots, $r = 0.57$, $p = 0.0136$) and the annual medians (squares, $r = 0.68$, $p = 0.0018$) of the Pier CHL anomalies also show an increasing trend. Thick black lines represent the linear regression analysis of the annual median values ($+0.076 \text{ mg/m}^3/\text{year}$ for the CHL anomalies).

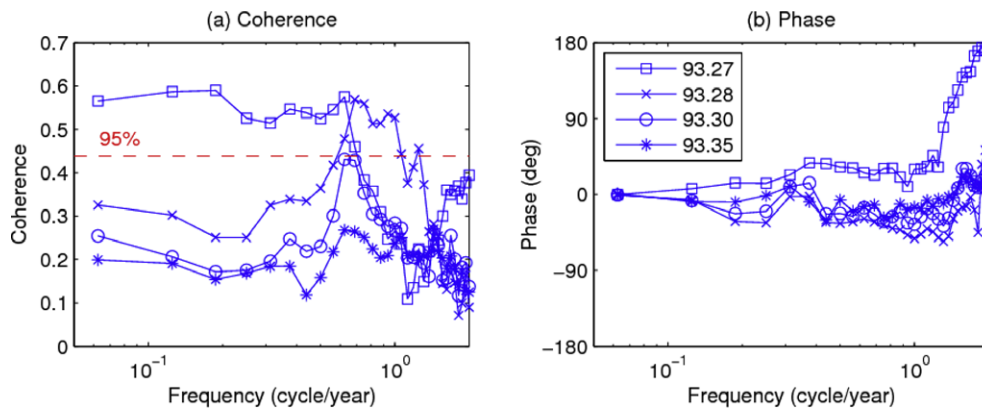


Fig. 13. Coherence (left) and phase (right) for the 17-year (1984–2000) surface chlorophyll time series measured at the Pier and nearby CalCOFI stations (Fig. 1). The coherence at low frequencies ($<0.5 \text{ cycle/year}$) is significant only for CalCOFI station 93.27. Distance between the Pier and 93.27 is roughly 12 km.

communities and mariculture operations. The source of the nutrients, the fate of the organic matter fixed, the extent of drawdown of CO_2 from the atmosphere during blooms and why, of the complex species community present, only a limited number of them bloom, are issues that need to be addressed in future work.

Our study shows that at our nearshore site the dynamics of phytoplankton growth and decline is different than that offshore. Both the mean standing crop and episodic blooms, although spatially coherent, are much amplified inshore compared to the offshore patterns. This characteristic of the nearshore blooms suggests that

a still undetermined physical forcing acts in the nearshore waters to supply the large input of nutrients necessary to support both the enhanced mean level of chlorophyll and the episodic blooms.

Whatever the forcing is for these patterns it does not appear to be local in origin. The lack of correlation with local SST anomalies or longshore winds or upwelling index indicates that classic coastal upwelling processes are not directly responsible, as does the lack of correlation with positive salinity anomalies. Nor does runoff from the land seem an important likely source of nutrients (Busse et al., 2006) since blooms at the Scripps Pier tend to occur in the

driest times of the year and are uncorrelated with negative sea surface salinity anomalies which do occur episodically, but only after occasional heavy winter rains and runoff. We do not understand the factors responsible for our observed patterns, but the on-shore–offshore and longshore continuity (from aerial surveys) of variations show that these are near-synchronous and of large spatial dimensions.

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