

---

# Phytoplankton blooms detected by SeaWiFS along the central and southern California coast

---

*Nikolay P. Nezlin, Martha A. Sutula, Richard P. Stumpf<sup>1</sup> and Ashmita Sengupta*

## ABSTRACT

The effect of upwelling events, stormwater discharge, and local circulation on phytoplankton blooms in the central California and Southern California Bight (SCB) coastal zones was analyzed using 10+ years (1997-2007) of remotely-sensed surface chlorophyll concentration (CHL, derived from SeaWiFS ocean color), sea surface temperature (SST, derived from AVHRR infrared measurements), and modeled freshwater discharge. Analysis of variability and factors associated with phytoplankton blooms was conducted using the offshore extension of zones of CHL  $>5 \text{ mg m}^{-3}$ , this method excludes terrestrial interference that complicates the use of ocean color to investigate phytoplankton blooms in coastal waters. In the SCB, blooms were most frequent in spring and associated with the spring transition to an upwelling regime. Along the Central Coast, blooms persisted from spring to autumn during seasonal intensification of upwelling. Offshore CHL extensions showed a significant positive trend during 1997-2007, with maxima in 2000-2001 and 2005-2006 that coincided with higher than normal frequency of upwelling events. Upwelling was found to be a major factor driving phytoplankton blooms, although the standard upwelling index derived from large-scale atmospheric circulation was decoupled from the frequencies of both upwelling events and phytoplankton blooms. Areas of longer residence time associated with natural boundaries between coastal ocean regions had more extensive

and persistent blooms. The influence of stormwater discharge on offshore CHL extension appeared to be limited to areas in close proximity to major river mouths. These locations, identified as bloom “hot spots,” were also co-located with ocean outfalls of Publicly Owned Treatment Works (POTW) discharge and, in some cases, longer residence time of coastal waters. This study successfully demonstrated the use of offshore CHL extension as an adequate measure of phytoplankton blooms in regions with narrow shelf and low freshwater discharge.

## INTRODUCTION

Increases in frequency and magnitude of phytoplankton blooms have been documented in many coastal ocean zones throughout the world (e.g., Gregg *et al.* 2005, Kahru and Mitchell 2008, Boyce *et al.* 2010). This trend has been viewed as a serious environmental concern, because phytoplankton blooms can result in hypoxia, shading of submerged aquatic vegetation, and toxin-producing harmful algal blooms (HABs; Anderson *et al.* 2002, Glibert *et al.* 2005). An apparent increase of phytoplankton blooms in general, and HABs in particular, throughout the world’s oceans is attributed to both climatic and anthropogenic factors, including the response of certain phytoplankton groups to global warming and increased nutrient loading (Glibert *et al.* 2006, Anderson *et al.* 2008, Heisler *et al.* 2008, Paerl and Huisman 2008).

---

<sup>1</sup>National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD

The relative importance of drivers to the increased frequency and duration of phytoplankton blooms in different coastal ocean regions is still unclear (e.g., Kahru *et al.* 2009). These factors can include: climate change, particularly change associated with intensification of natural upwelling (Bakun *et al.* 2010); increased anthropogenic loading of nutrients via terrestrial and groundwater runoff (Nixon 1995, Paerl 1997); wastewater discharge (National Research Council 2000); and atmospheric deposition (Paerl 1997). In eastern boundary current systems such as those found in coastal California, vertical wind-driven nutrient flux (upwelling) is known to be a dominant factor in controlling primary productivity (Barber and Smith 1981). Also, it is widely held among coastal resource managers that terrestrial nutrient sources are a relatively minor factor in comparison with upwelling, even when those sources are elevated from anthropogenic inputs in highly urbanized coastal areas such as the Southern California Bight (SCB), a region that contains 25% of the US coastal population (Culliton *et al.* 1990). Better understanding of the relative importance of the magnitude and timing of various nutrient sources, as well as knowledge of how ecological factors, including: oceanic circulation, frequency and duration of upwelling events, water residence time, and depth, might control biological responses to nutrient sources are necessary for improved management of environmentally important coastal areas like California.

Satellite remote sensing of ocean color is a powerful method for analyzing seasonal cycles and interannual trends in phytoplankton biomass (e.g., Banse and English 1994, Longhurst 1995, McClain 2009). Its use has been problematic in coastal waters, where traditional methods may be subject to significant inaccuracies and lead to inaccurate conclusions (e.g., Gregg and Casey 2004). In particular, the standard algorithms of ocean color data processing (O'Reilly *et al.* 1998) developed for clean open ocean waters usually overestimate chlorophyll in shallow near-shore zones because of the presence of colored dissolved organic matter and suspended matter (e.g., Muller-Karger *et al.* 2005). Another important factor leading to overestimation of chlorophyll in shallow waters is bottom reflectance, which depends on bathymetric depth and water transparency (e.g., Maritorena *et al.* 1994, Cannizzaro and Carder 2006). In narrow coastal zones, remotely-sensed signals may be

contaminated by landmass reflection (“adjacency effect” of atmospheric diffuse transmittance, Santer and Schmechtig 2000) and terrigenous absorbing aerosols (Moulin *et al.* 2001, Claustre *et al.* 2002, Ransibrahmanakul and Stumpf 2006). Consequently, the use of remotely sensed ocean color to understand spatial and temporal patterns in phytoplankton blooms requires alternative methods that circumvent terrestrial interferences.

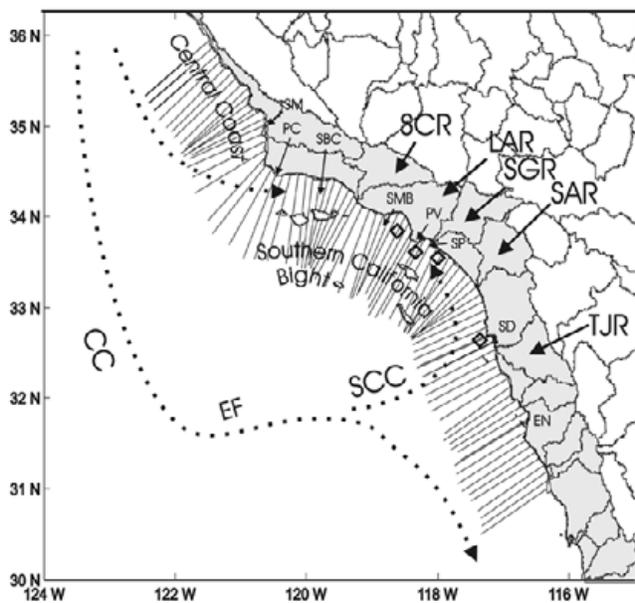
In this study, we use offshore extension of the zones of high remotely-sensed chlorophyll concentration (CHL) to study spatial and temporal patterns in phytoplankton blooms in narrow coastal areas along the central and southern California coastline. The objectives were to: 1) demonstrate the offshore extension of the zone of high remotely-sensed chlorophyll concentration as a measure of phytoplankton blooms in the regions characterized by narrow continental shelf and low terrestrial discharge; 2) characterize the magnitude, extent, seasonal, and interannual variability of phytoplankton blooms in central and southern California; and 3) compare the effect of different environmental factors (upwelling, stormwater discharge, and oceanic residence time) on offshore extensions of these blooms.

## METHODS

### Study Area: Central and Southern California Coast

The SCB is typically defined as the area from Point Conception (34.45°N) to the Mexican border (32.53°N). To compare phytoplankton variations in the SCB to areas to the north and south, we defined the study region as 31°N–36°N (Figure 1), including the southern part of the central California coast (from Lopez Point to Point Conception) and the northern Baja California down to Cabo Colnett, the southern boundary of upwelling zone (Schwing and Mendelsohn 1997).

Coastal circulation in the SCB is part of a large-scale circulation pattern, dominated by the cold equatorward California Current (CC) flowing from the north (Figure 1). This meandering current divides the CC ecosystem into a productive nearshore region and an oligotrophic offshore region (Hayward and Venrick 1998). To the north of Point Conception, the coastline is directed from the north to the south, and stable equatorward winds generate coastal upwelling. To the south of Point Conception, the coastline turns eastward forming the basin called SCB. The bottom



**Figure 1.** Transects along the central and southern California coastline where offshore CHL extension was assessed. Dotted lines indicate circulation in the Southern California Bight (SCB): California Current (CC), Ensenada Front (EF), Southern California Countercurrent (SCC). SM—Santa Maria; PC—Point Conception; SBC—Santa Barbara Channel; SMB—Santa Monica Bay; PV—Palos Verdes Peninsula; SP—San Pedro Shelf; SD—San Diego; EN—Ensenada. Watersheds draining to the ocean are shadowed. Major watersheds: SCR—Santa Clara River (includes also Calleguas Creek); LAR—Los Angeles River; SGR—San Gabriel River; SAR—Santa Ana River (includes also San Diego Creek); TJR—Tijuana River. Major POTW outfalls (diamonds) are located in SMB, PV, SP and SD.

topography of SCB consists of ranges of submarine mountains and valleys and is neither classical continental shelf nor continental slope (Emery 1960). The basins between ridges are rather deep (>500 m) and the SCB is bordered by a narrow shelf 3- to 6-km wide. Within the SCB, the CC stream turns to south-southeast (Figure 1) and passes along the continental slope. At about 32°N, a branch of the CC turns eastward and splits as it approaches the coast (Haury *et al.* 1993, Chereskin and Niiler 1994). The main core continues equatorward along the Baja California coast, while the rest recirculates poleward along the SCB coast (Harms and Winant 1998, Bray *et al.* 1999) and forms a large gyre known as the Southern California Eddy. The near-shore poleward branch of this eddy is called Southern California Countercurrent (SCC) (Sverdrup and Fleming 1941).

Seasonal variations of oceanic conditions in the study region are characterized by dramatic changes

in the spring. These changes are referred to as the “spring transition” and include the sudden (during approximately one-week period in March–April) onset of the spring/summer upwelling regime in the coastal ocean (Strub *et al.* 1987a,b; Bograd *et al.* 2009). In the spring, atmospheric conditions over eastern north Pacific abruptly change, forming a high-pressure system centered at 45°N:140°W and a low-pressure cell over the southwest continental United States that results in consistently intensive equatorward winds alongshore (Strub and James 1988). According to traditional views, the intensity of the equatorward CC increases, compared to the poleward SCC, in the spring, and its jet migrates onshore while its eastward branches penetrate into the SCB (Hickey 1979, Bray *et al.* 1999). Later in summer, the CC jet migrates offshore, where it remains until winter (Reid and Mantyla 1976, Bray *et al.* 1999, Haney *et al.* 2001), while the warm SCC penetrates further to the north and west within the SCB. However, a more recent study (Lynn *et al.* 2003) did not observe onshore migration of CC during the spring transition. Instead, a coastal upwelling jet was observed to develop independently of the CC; later this jet evolved offshore and regenerated the CC core. Seasonal intensification of coastal upwelling enriches the upper euphotic layer with nutrients and substantially increases its primary production (Barber and Smith 1981). Earlier studies have documented intensive upwelling along the Central Coast from April through September (e.g., Bakun and Nelson 1991) and weak all-season upwelling in the SCB (Winant and Dorman 1997). According to Lynn and Simpson (1987), regular spring coastal upwelling in the SCB is limited to a small region around Pt. Conception and the northern portion of the SCB; on this basis Mantyla *et al.* (2008) conclude that phytoplankton growth in southern California’s coastal waters must be supported by nutrient input other than coastal upwelling or advection.

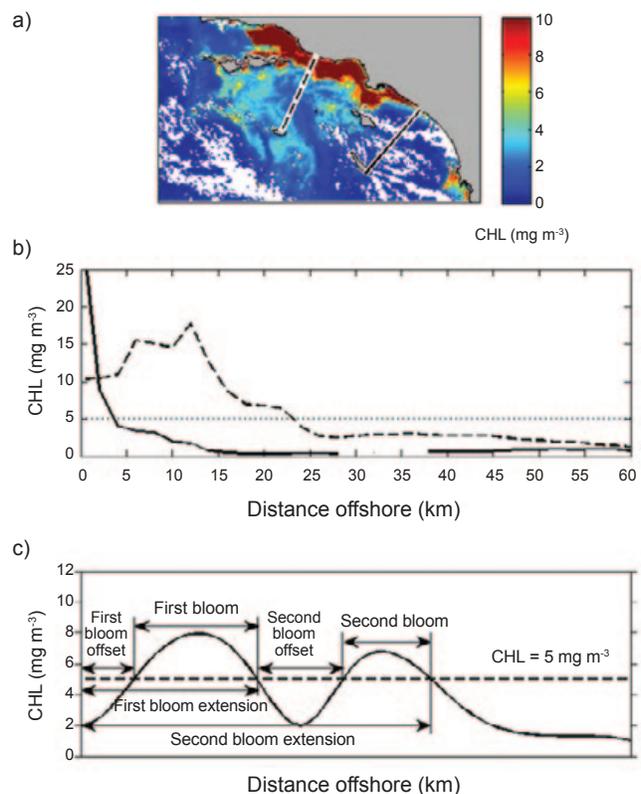
Another potential source of nutrients for phytoplankton growth in the SCB coastal zone is stormwater discharge, resulting from episodic storm events that typically occur between late fall and early spring. The study region has a Mediterranean climate, with an average annual rainfall of 10–100 cm (e.g., Nezlin and Stein 2005), falling primarily during winter months (December through March), and approximately 20 annual storm events (Ackerman and Weisberg 2003). Winter runoff to the

SCB contributes more than 95% of the total annual runoff volume (Schiff *et al.* 2000, Ackerman and Weisberg 2003). The coastal watersheds that drain to the SCB are comprised of approximately 14,000 km<sup>2</sup> (Figure 1) with urban and agricultural land uses (Ackerman and Schiff 2003). Although previous studies (Warrick *et al.* 2005) have documented low contributions from stormwater nutrient discharge to the total nutrient budget of SCB coastal waters, even during wet years (e.g., 1998) when stormwater discharge was assessed to have been two orders of magnitude higher than other years, the influence of freshwater discharge on phytoplankton growth is uncertain and needs further clarification to more fully understand how stormwater runoff affects physical stratification and circulation, suspended sediments, and the concentration and spatial distribution of nutrients, especially in the vicinity of river mouths.

In addition to nutrient loading attributed to winter runoff, POTW discharge is another potential nutrient source (Figure 1); the nutrient contribution of total POTW effluent to the SCB is comparable with stormwater runoff (total discharge in 2000 >45,000 mt, Lyon and Stein 2009). In contrast to highly seasonal stormwater discharge, POTW flow continues all-year round. In this study, the locations of anthropogenic nutrient sources (major river mouths and four major POTWs) were factored into data interpretation.

### Offshore Extension of Remotely-Sensed Chlorophyll (CHL) as a Measure of Phytoplankton Blooms in the SCB

Because this study is focused on the narrow near-shore coastal ocean zone, the approach used is based on the assumption that the influence of land interferences on the ocean color signal (measured by satellite sensor) dramatically decreases within a short (few kilometers) distance offshore. Thus, when the offshore CHL extent increases (i.e., during bloom events), there is an increased likelihood that phytoplankton pigments are responsible for the ocean color signal, as compared with suspended sediments, colored dissolved organic matter (CDOM), land and bottom reflection, etc. Average CHL in the narrow near-shore zone may include pixels located at the ocean-land edge where ocean color is most corrupted. This approach is illustrated in Figure 2ab, where two offshore transects represent high (dashed line) vs. low phytoplankton biomass (solid line). Even in the absence of bloom activity,



**Figure 2.** SeaWiFS CHL image (March 24, 2002; 19:56 UTC) with offshore transects in the bloom zone (dashed line) and away from the bloom (solid line) (a); CHL along these two offshore transects (solid and dashed lines in panels (a) and (b) correspond) (b); schematic sketch illustrating the method of assessment of offshore CHL extension (c).

the absolute value of CHL in narrow near-shore zones exceeds CHL in the bloom zone; this may be attributed to the effect of land proximity (land and bottom reflection, suspended sediments, CDOM, etc.), rather than high phytoplankton biomass. At the same time, the offshore extension of the zone of high CHL concentration (>5 mg m<sup>-3</sup>) in bloom zone is significantly larger than in the near-shore zone (~23 km vs. ~3 km; Figure 2b).

This method of characterizing offshore CHL extension in the SCB was used to analyze ocean color data collected by Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) onboard OrbView-2 satellite from November 7, 1997 to October 31, 2007. All satellite overpasses along the US West Coast were processed for CHL using OC4 algorithm (O'Reilly *et al.* 1998) and standard atmospheric correction methods (Gordon and Wang 1994). We preferred standard method of ocean color data processing because we believe that it adequately describes CHL

over most of the SCB (characterized by narrow shelf and low terrestrial discharge) excluding the pixels at the ocean-land edge. An alternative approach was not selected because processing ocean color data using specific methods developed for optically shallow waters may improve CHL assessment in the narrow near-shore zone, but decrease CHL accuracy in the rest of the study area.

The Level 2 CHL images (i.e., the data in sensor coordinates) were transformed into Level 3 maps (i.e., regular grids of 29°N–39°N:130°W–115°W with 1-km resolution in pseudo-sinusoidal projection for a total 6003 files).

To estimate the zone of offshore CHL extension, CHL data were averaged (as medians) in circular regions with 5-km radii located at 2-km intervals along 100-km offshore transects (Figure 1). In total, 85 transects were located 10 km apart along the coast, from 31°N to 36°N. The direction (azimuth) of each transect was normal to the direction of the 100-km part of the coastline centered at the transect/coast intersection. Medians instead of arithmetic means were used because CHL distribution in the ocean is asymmetric (Banse and English 1994, Campbell 1995), and medians are much closer to modal values than means.

In this study, a CHL “bloom” zone was defined as an area with CHL concentration  $>5 \text{ mg m}^{-3}$ . The CHL threshold of  $5 \text{ mg m}^{-3}$  was selected on the basis of its total statistical distribution; this threshold is approximately the 85<sup>th</sup> percentile of the entire 10-year CHL dataset within the 5-km near-shore area. In SCB, the location of  $5 \text{ mg m}^{-3}$  is close to (and may be treated as) a CHL frontal boundary, because similar analysis done with other thresholds (e.g., 4 or  $3 \text{ mg m}^{-3}$ ) resulted in different absolute values but almost identical temporal and spatial patterns. For each transect, the offshore extension of the CHL “bloom” zone (measured in km) was calculated. Because phytoplankton blooms can be spatially patchy and include several areas with  $\text{CHL} > 5 \text{ mg m}^{-3}$ , the bloom zone nearest to the coastline was defined as “coastal” and included in the analysis when its offshore offset (i.e., the distance between the coast and the bloom) did not exceed 5 km. The extent of additional bloom patches was added to the extent of the first one when the offset between the first and the second bloom zones did not exceed 10 km (Figure 2c).

To analyze bloom seasonality, daily CHL extensions offshore in each region were averaged for each day (1 - 365), and the seasonal cycles were

smoothed using a 1-month (31-day) cosine-filter. Here and below, the size of smoothing filter windows were selected by trial-and-error and based on the criteria of the best interpretation of the results.

Interannual variability was analyzed after smoothing daily offshore CHL extensions using a 1-year (365-day) cosine-filter. To test for trends in offshore CHL extension, Sen’s Nonparametric Estimator of Slope (Sen 1968) was used. This robust estimator allows missing data, makes no assumptions on data distribution, and is not affected by gross data errors and outliers. Trends were computed from decimated (set to 10-day intervals) smoothed data. Statistical significance of the trends was tested by calculating the ranks for the upper and lower confidence intervals using Mann-Kendall statistic and normal Z-statistic. The median slope was defined as statistically different from zero (for the selected 95% confidence interval) if the zero did not lie between the upper and lower confidence limits.

### **SST Anomalies as a Measure of Upwelling Events and Residence Time**

Upwelling events along the California coast were analyzed on the basis of daily sea surface temperature (SST) infrared data collected by Advanced Very High Resolution Radiometers (AVHRR) in 1997–2007 and processed by Pathfinder (Version 5) project (Kilpatrick *et al.* 2001). The dataset was obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) Ocean Earth Science Information Partners Program (ESIP) Tool (POET) website as regular grids of 4.5-km spatial resolution in equidistant cylindrical projection. Daytime and nighttime SST data were merged using averaging method (see Gregg 2007). Mean SST were estimated for each day for 85 regions with 10-km radii located at intersections between the offshore CHL transects (see section 2.2) and the coastline.

Upwelling events were defined as the periods of abrupt SST decrease. For this, SST variations in each coastal region were split among three types of variation in frequency range: 1) seasonal variability (climatology over a 1-year period); 2) low-frequency “background” variability; and 3) high-frequency variability, assumed to be associated with upwelling events. Seasonal SST climatology was estimated by averaging SST for each day (1–365) during 1997–2007 and smoothing the resulting time-series with a 1-month (31-day) cosine-filter. After subtraction of climatology, the resulting time series

(seasonal anomalies) for each region were linearly interpolated for daily intervals (to fill missing data) and split between low-frequency “background” SST variations (SST seasonal anomalies smoothed using a 365-day cosine filter) and the remaining high-frequency SST variations. The days when the high-frequency SST component was  $<-1.5^{\circ}\text{C}$  (total 2.75% of observations) were classified as “upwelling events”. This method appeared to be more accurate during seasonal SST increases and less accurate during the second half of the year when abrupt temperature drops were thought to be associated with factors other than upwelling (see results). Seasonal patterns of “upwelling frequency” were calculated for each day and smoothed using 2-month (61-day) cosine-filter. Interannual variability was analyzed after smoothing the data with a 365-day cosine-filter.

Offshore CHL extension and high-frequency SST variations were used for a coarse evaluation of residence time along the SCB coast. The coefficients of correlation ( $R^2$ ) between short-term SST seasonal anomalies and offshore CHL extensions in the 85 analyzed regions/transects were calculated on the basis of the entire period of observations (1997–2007). We hypothesized that correlations in SST and CHL indicate an interchange between these regions: high correlations are associated with intensive circulation and short residence time, while low correlations were associated with sluggish circulation and long residence time within natural boundaries. Using the term “residence time” we are aware of the difference between our assessment and quantitative estimation of water residence time in coastal waters and estuaries (e.g., Ketchum 1951).

The frequency of upwelling events was compared to the upwelling index (UI) in central and southern California calculated at the Pacific Fisheries Environmental Laboratory (PFEL) from the intensity of upwelling-favorable wind. The methodology of PFEL UI assessment is based upon Ekman’s theory of mass transport due to wind stress. The intensity of offshore water transport was calculated every six hours from a global field of atmospheric pressure at sea level of  $1^{\circ}$  spatial resolution. Monthly UI and UI anomalies ( $\text{m}^3 \text{s}^{-1}$  per 100 meters of coastline) at  $33^{\circ}\text{N}$ ,  $119^{\circ}\text{W}$  and  $36^{\circ}\text{N}$ ,  $122^{\circ}\text{W}$  were obtained from PFEL website (<http://www.pfeg.noaa.gov/>).

The intensity of upwelling events and phytoplankton blooms were compared to the North Pacific Gyre Oscillation (NPGO) climatic index (Di

Lorenzo *et al.* 2008), which measures changes in the North Pacific gyres circulation; its maxima are associated with upwelling-favorable and minima with upwelling-unfavorable conditions to the south of  $38^{\circ}\text{N}$ . The data were obtained from the NPGO website (<http://www.o3d.org/npgo/>).

Twenty-eight major upwelling events were selected for analysis of their effect on phytoplankton blooms. Upwelling events were estimated from a continuous (at 1-h intervals) record of ocean surface temperature obtained by the national Data Buoy Center (NDBC) mooring 46025 in the Santa Monica Bay ( $33.749^{\circ}\text{N}$ : $119.053^{\circ}\text{W}$ ; depth 905.3 m; 33 NM offshore). The time series was analyzed in a way similar to AVHRR SST (i.e., split into seasonal, long-term, and short-term variations). The days when at least 50% of temperature measurements were  $1.5^{\circ}\text{C}$  lower than background (i.e., seasonal plus long-term components) were classified as “upwelling events”. Offshore CHL extensions were averaged for the days referenced to the beginning of upwelling event.

### **Precipitation and Stormwater Runoff**

Continuous flow data only exists for a small percentage of all rivers that discharge into the SCB. Therefore, daily stormwater runoff  $Q$  ( $\text{m}^3 \text{day}^{-1}$ ) was modeled using the Rational Method (O’Loughlin *et al.* 1996), a spreadsheet model that is based on optimized runoff coefficients in conjunction with the watershed land-use pattern and the estimated averaged rainfall.

The Rational Method is similar to the EPA’s Simple Method, though events with no runoff are excluded from the Rational model, which estimates runoff as a function of drainage area ( $A$ ,  $\text{km}^2$ ), mean rainfall intensity ( $I$ ,  $\text{mm day}^{-1}$ ), and the runoff coefficient ( $C$ ):

$$Q = A \cdot I \cdot C$$

The drainage area  $A$  was defined using the hydraulic unit code (HUC), and watershed areas larger than  $52 \text{ km}^2$  upstream of dams were removed from the model domain (Ackerman and Schiff 2003). Extensive land-use information available was sorted into six categories: agriculture, commercial, industrial, open, residential, and other urban. The sorted land-use data was used to characterize the drainage area.

Daily precipitation  $I$  in central and southern California from January 1997 through December

2007 was calculated on basis of the data obtained from the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS) National Climatic Data Center (NCDC) Climate Data Online (CDO) database (<http://www7.ncdc.noaa.gov/CDO/cdo>). Daily measurements collected by ~200 rain gauge stations were downloaded and transformed to mean precipitation (cm day<sup>-1</sup>) over 98 southern California watersheds from Pt. Conception to Mexican border. For this, all available precipitation data were interpolated within each watershed on a regular grid using a Biharmonic Spline Interpolation method (Sandwell 1987). The watersheds were divided in grids with a minimum 5 rows/columns (grid resolution  $\leq 0.02$  degrees); for the larger watersheds, where 5 rows/column grids resulted in a coarser resolution, larger grids were used, keeping the grid resolution constant at 0.02 degrees.

The runoff coefficient  $C$  assigned to watersheds varied with topography, land-use, vegetal cover, soil type, and soil moisture content. A bounded iterative optimization was used to determine runoff coefficients from measured local runoff. The goal of this optimization was to produce a set of runoff coefficients for each land-use type within the SCB (Ackerman and Schiff 2003). In cases for which land-use varied within a watershed, segments of the watershed with different land-use were estimated individually. Resulting interannual variations were smoothed using a 183-day square filter.

To compare the effect of stormwater runoff and upwelling events on phytoplankton blooms, 23 major storms were selected and analyzed in conjunction with 28 major upwelling events (see above). For each storm event, accumulated precipitation exceeded 2.5 cm. The offshore CHL extensions were averaged for the days referenced to the beginning of rainstorm.

## RESULTS

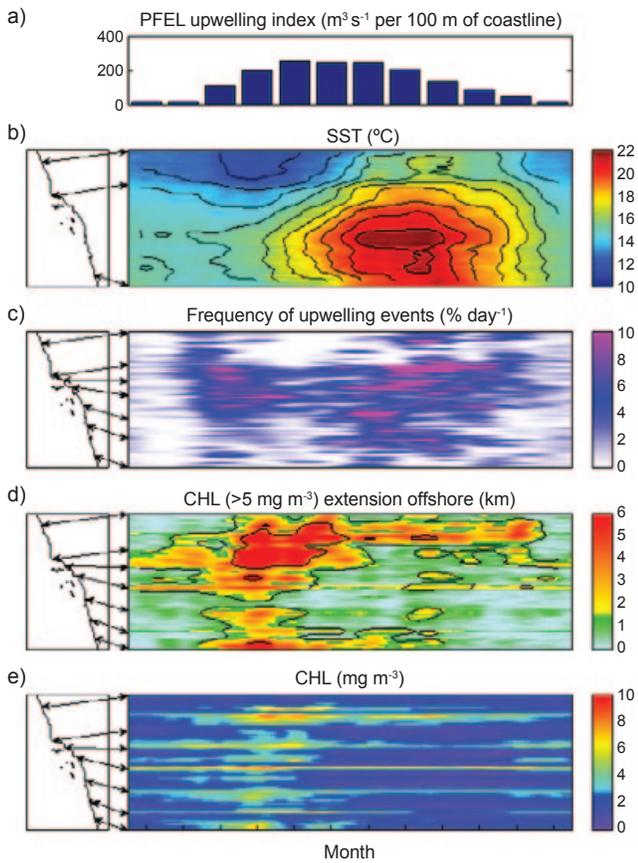
### Seasonal and Spatial Patterns

The characterization of offshore CHL extension adequately captured most bloom events. In the SCB, bloom zones were observed mostly nearshore. Only in the Santa Barbara Channel did the “first” bloom offset regularly exceed 5 km, which could be attributed to the zones of high CHL around the Channel Islands (not shown). Correspondingly, the

near-shore bloom events were regularly observed along the entire SCB coastline. The “second” (offshore) bloom zones (see Figure 2C) were scarce and observed mostly around the Channel Islands. Nearshore bloom “hotspots” (the regions where CHL extension offshore was measurable throughout most of the year) included areas near Santa Maria (Central Coast), the Santa Barbara Channel, Palos Verdes Shelf, San Pedro Bay, South San Diego, and Ensenada (Figure 3D).

Along the Central Coast, blooms began roughly in April and lasted until November, especially near Santa Maria. Blooms in this region tended to be large (>6 km offshore), particularly in the spring. Initiation of blooms in the spring coincided with seasonal intensification of coastal upwelling-generating winds (Figure 3A). Spring intensification of coastal upwelling along the Central Coast was evident from seasonal SST minima (Figure 3B), which to the north of Pt. Conception occurred approximately two months later than in the SCB (April vs. February). Along the Central Coast, the frequency of short-term upwelling events was low all year round (Figure 3C). In contrast to the SCB, this indicated steady oceanographic conditions, in contrast to the SCB. During the summer, a steady upwelling regime along the Central Coast was evident from the SST (Figure 3B), which was significantly lower than in the SCB, coinciding with high intensity of upwelling-favorable winds (cf. Figure 3A).

South of Point Conception, blooms generally started in the spring and lasted two to three months throughout most of the SCB, extending as far as 6 km offshore during the bloom peak (typically in April). Blooms were most pronounced in the Santa Barbara Channel, Santa Monica and San Pedro Bays, and along the northern Baja California coast (Figure 3D). Initiation of blooms in the spring were associated with spring transition, when upwelling-favorable winds strengthened (Figure 3A) and upwelling events started in the northern and central parts of the SCB (Figure 3C). The frequency of upwelling events in this area was high from February to October. In the southern part of the SCB, upwellings were frequent from June to August. The SCB demonstrated more intensive upwelling in fall as compared with spring (Figure 3C), which appears to be counterintuitive and attributable to inaccurate removal of seasonal variability in the data set. During the period of temperature increase (February–July), temperature



**Figure 3. Seasonal variability along the central and southern California coast: PFEL upwelling index at 33°N ( $\text{m}^3 \text{s}^{-1}$  per 100 m of coastline) (a); SST (b); frequency of upwelling events ( $\% \text{day}^{-1}$ ) (c); the zone of high CHL ( $>5 \text{ mg m}^{-3}$ ) offshore extension (km) (d); CHL concentration averaged over 5-km inshore parts of the transects (e).**

drops were associated mostly with upwelling events, while during the period of temperature decrease (August–February) short-term SST decreases may have resulted from short periods of seasonal cooling that were more intensive than the smoothed seasonal SST cycles used in this study.

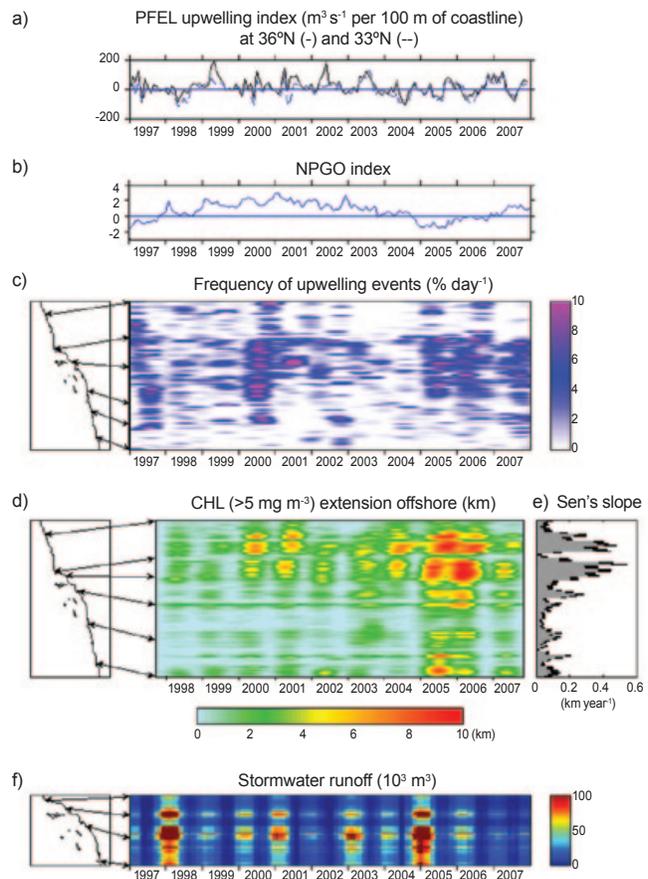
The averaged CHL within the 5-km near-shore regions (Figure 3E) demonstrated seasonal patterns that were similar to, but less obvious than, those of corresponding offshore CHL extensions (Figure 3D). In particular, CHL zones proximal to major river mouths showed a summer minima and winter maxima that coincided with the timing of seasonal stormwater runoff maxima.

### Interannual Variations

An increasing trend of offshore CHL extension was observed during 1997–2007 for both the Central Coast and the SCB (Figure 4D, E). The most evident

growth of the zone of high CHL was observed in the southern part of the Central Coast, the Santa Barbara Channel, Santa Monica Bay, and San Diego ( $0.2 - 0.4 \text{ km year}^{-1}$ ). Almost all trend assessments (excluding Pt. Conception) were statistically significant with a 95% confidence level, which could be attributed to the large number of observations (371).

Similar analysis performed on averaged CHL in the 5-km near-shore regions also demonstrated a significant positive trend (not shown). In contrast to offshore CHL extensions, these trends were most pronounced near the river mouths, where remotely-sensed CHL concentration was likely to be measured most inaccurately. Surprisingly, these positive trends could not be attributed to stormwater runoff variations, as stormwater runoff demonstrated small



**Figure 4. Interannual variability along the central and southern California coast: PFEL upwelling index ( $\text{m}^3 \text{s}^{-1}$  per 100 m of coastline) at 36°N (solid line) and 33°N (dashed line) (a); NPGO index (b); frequency of upwelling events ( $\% \text{day}^{-1}$ ) (c); the zone of high CHL ( $>5 \text{ mg m}^{-3}$ ) offshore extension (km) (d); CHL extension offshore positive trend (black bars–Sen's slope;  $\text{km year}^{-1}$ ; grey bars–5% lower confidence intervals) (e); Stormwater runoff ( $10^3 \text{ m}^3 \text{ day}^{-1}$ ) (f).**

(100 - 3000 m<sup>3</sup> year<sup>-1</sup>), but significant negative trends over the entire study area (not shown).

At a large spatial scale (i.e., within the entire study area), most intensive upwelling events and phytoplankton blooms were observed simultaneously. Compared to other years, larger offshore CHL extensions were observed in summer 2000-2001 along the Central Coast, in summer 2004 along the Central Coast and in the Santa Barbara Channel, and in summer 2005-2006 throughout the entire study region. Most of these periods (2000-2001 and 2005-2006) were characterized by high frequency of upwelling events in the SCB. Only in 2004 were higher than normal phytoplankton blooms not coinciding with higher than normal upwelling intensity observed in the northern part of the study area (Figure 4A, C). Notably, periods of greatest frequency of upwelling events in SCB coincided with extremes in the NPGO cycle: positive in 2000-2001 and negative in 2005 (Figure 4B).

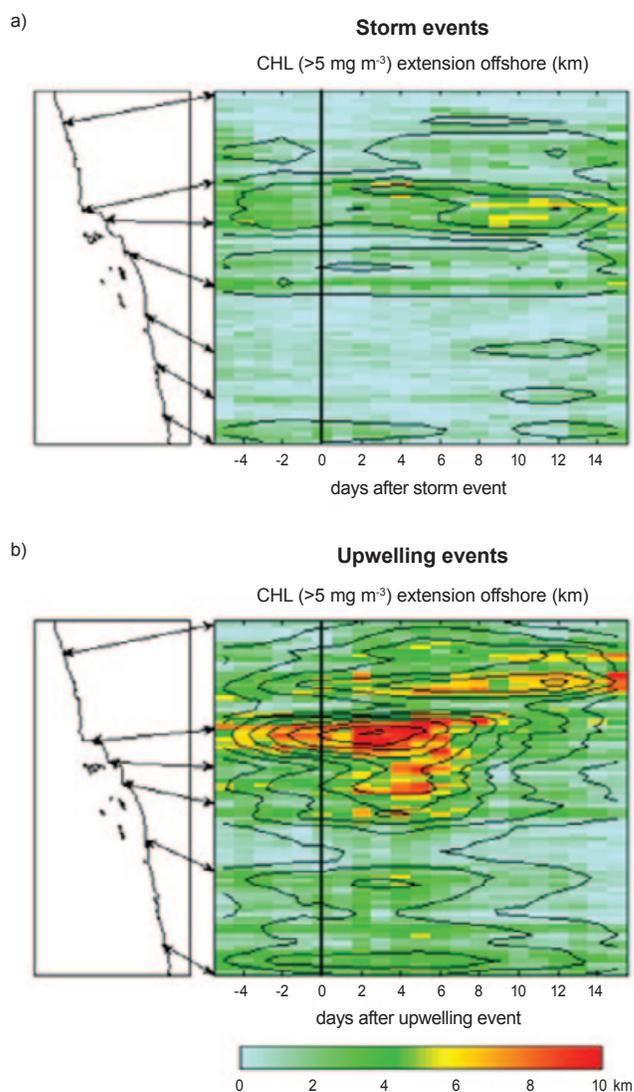
The effect of the interannual variability in stormwater runoff on the intensity of coastal phytoplankton blooms bightwide was less evident compared to upwelling. Runoff was higher than normal during the winter/spring of 1997-1998 and 2004-2005 (Figure 4F). Stormwater runoff during 2004-2005 coincided with the beginning of intensive upwelling and most intensive phytoplankton blooms both along the Central Coast and in the SCB. However, torrential rains in 1997-1998 (El Niño year) and resulting intensive runoff did not correspond to an increase in offshore CHL extension. During the rest of the observed period, stormwater runoff appeared to coincide with increased offshore extension of blooms in those areas proximal to the mouths of major rivers. The latter, however, could be partly attributed to the confounding effect of stormwater plumes on ocean color rather than phytoplankton blooms.

### Factors Affecting Blooms: Upwelling, Stormwater Runoff and Local Circulation

Analysis of 23 major storm events and 38 upwelling events supports the hypothesis that upwelling was the dominant factor affecting phytoplankton blooms in the SCB and along the Central Coast. Our analysis suggested that the role of stormwater runoff in promoting phytoplankton blooms was more likely limited to areas proximal to river mouths.

After major upwelling events, zones of high CHL extended by 10 km offshore (Figure 5B) for 5 to 8 days in the SCB and for at least 15 days along the Central Coast. In the Santa Barbara Channel, phytoplankton blooms started to appear 4 days before the date designated as the “upwelling event” (i.e., an abrupt decrease of the surface water temperature in the Santa Monica Bay) in this study. This time lag characterizes the spatial pattern of upwelling and resulting bloom development throughout the SCB from the north to the south.

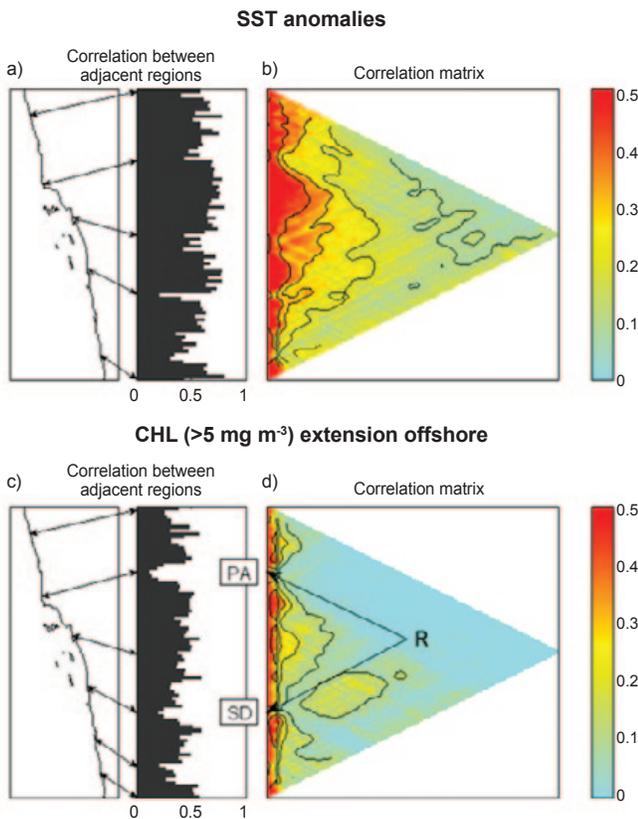
After storm events, only a slight increase (by 2 km) in offshore CHL extension was observed for 8 to 14 days in “hotspot” areas close to river mouths (Santa Clara/ Calleguas, Los Angeles/San Gabriel,



**Figure 5.** The zone of high CHL (>5 mg m<sup>-3</sup>) offshore extension (km) along the central and southern California coast after major rainstorms (a) and after major upwelling events (b).

Santa Ana/San Diego Creek and Tijuana Rivers; Figure 5A). Similarly, offshore CHL extensions increased by 5 km 5 to 15 days after storms in the Santa Barbara Channel.

Upwelling events affected the entire study region, including SCB and the Central Coast, rather than its parts. The correlation ( $R^2$ ) among short-scale SST seasonal anomalies in different parts of the study area (Figure 6B) substantially exceeded the correlation among offshore CHL extensions (Figure 6D). Also, correlations among SST in adjacent regions were not always high; for these locations, low correlation was attributed to low intensity of horizontal mixing. Such “natural boundaries” were observed near Pt. Conception, Santa Monica Bay, Palos Verdes Peninsula and San Diego (Figure 6A). A similar pattern was observed in variability in offshore CHL extension (Figure 6C): low correlation



**Figure 6.** Correlations (coefficients of determination  $R^2$ ) between (a, b) short-term SST seasonal anomalies and (c, d) offshore CHL extension along the central and southern California coast. Correlations between adjacent regions/transects (a, c); correlations between all regions/transects (b, d). Horizontal axes in (b) and (d) are roughly proportional to the distance between the regions. In particular, location R in (d) indicates the correlation between Point Arguello (PA) and San Diego (SD).

was observed near Pt. Conception, San Diego, and Ensenada. In most of these regions, the frequency of CHL blooms was higher than in other parts of the SCB (Figures 3D and 4D).

## DISCUSSION

### Offshore CHL Extension as a Bloom Indicator

Climatological patterns of phytoplankton biomass are often examined on the basis of averaged remotely sensed CHL concentrations (e.g., Banse and English 1994, Longhurst 1995, McClain 2009). The results, however, are influenced by the accuracy of the estimated chlorophyll concentration of every pixel, which results in overestimation of phytoplankton biomass in the near-shore ocean zone, where ocean color signal can be biased by sediment loads in river plumes, unusual amounts of CDOM, bottom and landmass reflection, etc. Quantification of these effects to correct remotely-sensed CHL concentration (e.g., Dall’Olmo *et al.* 2005, Cannizzaro and Carder 2006, Ransibrahmanakul and Stumpf 2006) is labor consuming and the accuracy of these methods is questionable.

Use of the offshore CHL extension method avoids erroneous conclusions associated with traditional approaches based on the absolute value of remotely sensed CHL. In particular, CHL near SCB river mouths demonstrated a seasonal cycle with a summer minimum and winter maximum corresponding to the seasonal magnitude of stormwater runoff, which was attributed to contamination of ocean color signal by suspended sediments and CDOM near river mouths (e.g., Nezlin *et al.* 2008) rather than phytoplankton productivity. In the analysis of interannual trends, CHL concentrations demonstrated a high positive trend only near river mouths. Conversely, removal of this effect through use of offshore CHL extension revealed a positive interannual trend over most of the study region. On a bigt-wide scale, seasonal patterns illustrated by the offshore CHL extension were similar to those documented by Hayward and Venrick (1998) in a 12-year time series of chlorophyll measurements conducted by the CalCOFI program in the far offshore zone.

While offshore CHL extension is a promising method, it is important to note that it does have some limitations. First, its use in the assessment of phytoplankton blooms is valid only in coastal regions like the SCB, with a narrow shelf and low

freshwater discharge (i.e., in the areas where land contamination of ocean color dramatically decreases offshore. Second, it is important to note that use of Level 3 satellite imagery of approximately 1-km resolution, appears appropriate for analysis of the bloom zone which has an order of magnitude of 5 - 10 km during bloom events and 0 - 2 km otherwise. Imagery of this resolution is not available now for most ocean color satellite data sources, and standard MODIS-Aqua and SeaWiFS Level 3 data (4.5 and 9 km, respectively) are too coarse for this purpose. Finally, the method of calculating offshore CHL extension depends on coastline configuration. The method may indicate “hotspots” in areas with a “concave” coastline (bays) where “land effects” have a greater impact on analysis due to larger shelf zones and the positioning of transect lines. These areas in the SCB often coincide with zones of sluggish circulation, making it difficult to distinguish the effects of these factors on offshore CHL extension as a bloom indicator.

### **Factors Associated with Offshore CHL Extension: Upwelling**

In the SCB and along the Central Coast, this study found that upwelling is a dominant factor associated with the frequency and magnitude of phytoplankton blooms. Upwelling in the northeastern Pacific is a large-scale phenomenon affecting the entire SCB, the Central Coast, and other areas. At a local scale, however, upwelling events and phytoplankton blooms were not always observed in parallel. In this study, during 2000–2001 upwelling events were detected in the SCB, while phytoplankton blooms were most evident along the Central Coast. This is possible because local surface measurements (including SST and ocean color) do not always indicate upwelling and bloom events when they happen. Upwelling does not always manifest itself in a decrease in SST, because cold upwelled water that enriches the upper euphotic layer with nutrients does not necessarily affect the surface layer if the water column is stratified. Most phytoplankton growth fueled by upwelling occurs in the 20 - 40 m subsurface layer (e.g., Reid *et al.* 1978; Cullen and Eppley 1981; Cullen *et al.* 1982, 1983; Millan-Nunez *et al.* 1996) which is not observed from satellites. Consequently, the surface signatures of upwelling and phytoplankton blooms can be spatially separated. Anderson *et al.* (2008) also noted an apparent synchrony of HAB

events in different California regions; they explained this synchrony with large-scale external forcing (primarily upwelling).

Along most of the SCB coast, interannual variability of offshore CHL extension demonstrated a significant positive trend during 1997–2007. Previous studies (e.g., Gregg *et al.* 2005, Kahru and Mitchell 2008) have reported an increase in remotely-sensed CHL in many coastal areas worldwide, including the California Current zone (Kahru *et al.* 2009). This increase may be related to climate change associated with intensification of seasonal upwelling (Bakun 1990, Bakun and Weeks 2004, Bakun *et al.* 2010), although its cooling effect may have been masked by a long-term increasing trend in SST (Schwing and Mendelssohn 1997). The latter was observed in this study for 1997–2007. No trends were revealed from low-frequency SST variability, and Sen’s slopes were negligible in most regions (average  $-0.003 \pm 0.026$  degrees C year<sup>-1</sup>). The increase in the offshore extension of phytoplankton blooms in the SCB captured over a 10-year time series is too short to understand the influence of climate change as a causal factor. Henson *et al.* (2010) indicate that a time series of ~40 years is needed to distinguish a global warming trend from natural variability. Surprisingly, no relationship was evident between the frequency of near-shore blooms in the SCB and the transition between the strong El Niño event in 1997–1998 and the 1998–1999 La Niña, which some authors called the most dramatic and rapid episode of climate change in modern times (Schwing *et al.* 2002, Peterson and Schwing 2003). In contrast, the effect of 1997–1998 El Niño on CHL was most clear within the 100-km offshore zone throughout the observed period (Thomas *et al.* 2009).

Periods of high intensity of upwelling and offshore CHL extension on an interannual scale coincided with both positive (in 2000–2001) and, surprisingly, negative (in 2005) extremes of NPGO climatic cycle (Di Lorenzo *et al.* 2008). A nonlinear relationship between NPGO and near-shore bloom activity in the SCB may be attributed to a weak correlation between upwelling and chlorophyll resulting from its complex bottom topography (cf. Thomas *et al.* 2009). Positive NPGO is associated with enhanced CC circulation, resulting in strong upwelling, nutrient enrichment, and phytoplankton growth along the entire East Pacific. The NPGO minimum (suggesting upwelling-unfavorable conditions) was observed in 2005. Surprisingly, it

was followed by the most intensive and long-lasting phytoplankton blooms in SCB coastal zone. These blooms might have been attributed to specific features of an upwelling regime along the U.S. West Coast; the spring transition in 2005 occurred two-three months later than during other years (Schwing *et al.* 2006, Bograd *et al.* 2009). However, in the latter part of the upwelling season, coastal upwelling was stronger than normal, resulting in positive CHL anomalies in the 0–100 km offshore zone between 30°N–40°N (Thomas and Brickley 2006, Henson and Thomas 2007). A pronounced biological effect of the variations of upwelling seasonality was demonstrated earlier in the CC (Black *et al.* 2011).

The 5–8-day time lags between the onset of upwelling events and increases in offshore CHL extension indicate that the observed phenomena may be attributed to biological (phytoplankton growth), rather than physical (shoaling of subsurface chlorophyll maximum) processes associated with upwelling. Notably, subsurface maximum of chlorophyll concentration is regularly observed (e.g., Millan-Nunez *et al.* 1996) at a depth of 20–40 m, which is invisible to satellite sensors. Upwelling-driven shoaling of this maximum can simultaneously affect SST and surface ocean color as observed from satellites. This physical effect implies a zero time lag between the decrease in SST and the increase in remotely-sensed CHL. In contrast, the biological effect of upwelling (nutrient flux to the euphotic layer fueling phytoplankton growth) implies a time lag of few days between upwelling events and phytoplankton blooms (see Henson and Thomas 2007 and the citations therein). The blooms observed in this study followed upwelling events with a 5-8-day time lag, similar to earlier observations (Nezlin and Li 2003).

No relationship was found between the frequency of upwelling events in SCB and the PFEL upwelling index (UI), which characterizes large-scale patterns of atmospheric circulation over the west coast of North America (Bakun 1973). This lack of correspondence can be attributed to complex bottom topography in the SCB, in contrast to areas to the north and south characterized by relatively straight coastlines with meridional direction coinciding with the direction of upwelling-favorable wind. The latter fits the classic scheme of Ekman upwelling, resulting in a straightforward relationship between large-scale wind patterns (UI), upwelling intensity, and phytoplankton growth. For example, in the

Oregon coastal zone, UI explains ~77% of the upwelling system's interannual variability (Pierce *et al.* 2006). In contrast, in the SCB, the results of this study indicated no relationship between UI and the frequency of upwelling events (cf. Thomas *et al.* 2009). Previous studies also indicated that wind stress explains little of the current variability within SCB (Lentz and Winant 1986, Noble *et al.* 2002, Hickey *et al.* 2003).

### **Other Factors Associated with Offshore CHL Extension**

The results of this study based on 10+ years of observations demonstrated no evidence of the regional importance of stormwater discharge for phytoplankton blooms in the SCB and along the Central Coast. In both 1997–1998 and 2004–2005, when precipitation and stormwater runoff were high, the phytoplankton response was variable. In 2004–2005, high precipitation was followed by intensive coastal upwelling and phytoplankton blooms. As such, stormwater discharge cannot be identified as the single source of these blooms. In 1997–1998 (El Niño year), phytoplankton blooms were scarce in spite of torrential rains and intensive runoff. The positive effect of stormwater nutrient discharge may have been counterbalanced by negative effect of stronger than normal nutrient limitation that resulted from El Niño-driven deep pycnocline (e.g., Chavez *et al.* 1998, 1999). Previous studies suggested that the contribution of river discharge to the nutrient budget in the SCB is small compared to upwelling (Warrick *et al.* 2005). On the other hand, nutrient contribution from terrestrial sources (including stormwater and dry weather runoff, groundwater discharge and atmospheric deposition) could be negligible at a large scale, but have a pronounced effect at a local scale, especially near river mouths and in shallow semi-enclosed basins characterized by long water residence time. In areas near river mouths and areas characterized by extended residence time, terrestrial discharge (rich in ammonia and micronutrients, e.g., iron) has been shown to enhance phytoplankton productivity and alter N:P:Si ratios that affect the taxonomic structure of phytoplankton (Paerl 1997).

Comparing the effects of storm and upwelling events on offshore CHL extension one should keep in mind that nutrient-rich storm runoff always enters the ocean at the surface and as such its effect would be observed by satellite sensors much better than upwelling and/or POTW discharge, which effect

may or may not reach all the way to the surface. Slight increase in offshore CHL after storm events as compared with upwelling accentuates the effect of upwelling on phytoplankton growth in the SCB.

In this study, we found “hot spots”. Hot spots were areas in which the offshore extension of blooms occurred. This occurred throughout most of the year in Santa Maria (Central Coast), the Santa Barbara Channel, along the San Pedro Shelf, in the Santa Monica Bay, along the South San Diego and Ensenada coast, and in areas with long residence time co-located with large river mouths and POTW ocean outfalls. Persistent high CHL in shallow semi-enclosed regions with long residence time has been documented in previous studies in the SCB and elsewhere. Cullen *et al.* (1982) suggested that the residence time of water near the coast is of great importance to the determination of the abundance and taxonomic characteristics of phytoplankton. In particular, coastal regions characterized by retentive circulation and stratified water column are often subject to intensive dinoflagellates blooms (e.g., Ryan *et al.* 2008). For example, dinoflagellate blooms with chlorophyll *a* concentrations as high as 500 mg m<sup>-3</sup> were recorded in La Jolla Bay in May–August of 1964–1966 and associated with a steep shallow thermocline (Holmes *et al.* 1967). In San Pedro Bay, a region characterized by long residence time, has recently had frequent blooms of *Pseudo-nitzschia spp.* and some of the highest concentrations of domoic acid ever recorded on the U.S. west coast (Caron 2008). In addition, Anderson *et al.* (2002) noted that in areas of poor flushing the toxic effect of HABs can be much more severe. However, the assessment of water residence time based on correlations among SST anomalies is not sufficiently accurate to evaluate the significance of the influence of local circulation on phytoplankton growth. The mechanism of this influence could be better analyzed using mathematical modeling (cf. Mitarai *et al.* 2009).

In the SCB, regions of poor flushing often coincide with river mouths and POTW locations and, as such, receive additional nutrient contributions. While the effect of stormwater discharge near major river mouths on offshore bloom extensions was limited relative to upwelling, river mouths can be a chronic, low-concentration source of nutrients through dry weather discharge; a factor not considered in this study. In the SCB’s Mediterranean climate, dry weather discharge has increased as

the landscape has become increasingly urbanized and supported by the import of freshwater from northern California and the Colorado River basin (Ackerman and Schiff 2003). Locally, the effect of this dry weather runoff can be substantial. Analysis of nutrient loads to the SCB demonstrated that dry-weather discharge from the Los Angeles and San Gabriel Rivers represents approximately 48% of total annual nitrogen loads to the San Pedro Bay area and 24% of total annual nitrogen loads to the entire SCB (A. Sengupta, unpublished data). Also, nutrient-rich wastewater discharge from large POTWs may be an additional continuous source of nutrients. All four large POTWs in SCB have outfalls where “hot spots” of high offshore CHL extensions were observed, but these outfalls are also located in areas characterized by shallow depth and long residence time, or in close proximity to river mouths.

We conclude that within the SCB, upwelling is a clear driver controlling spatial and temporal patterns of remotely-sensed phytoplankton productivity. On a more refined spatial scale, terrestrial freshwater discharge and POTW discharges via ocean outfalls have the potential to affect patterns of phytoplankton productivity, particularly by increasing the duration and size of the blooms. However, a remote sensing analysis of factors associated with the spatial and temporal patterns in phytoplankton blooms in the SCB cannot effectively distinguish between the effects of wastewater, stormwater discharge, bathymetry, and water residence time. To quantify the relative influence of these nutrient sources, mathematical modeling, supported by real-time monitoring and regular surveys collecting oceanographic data, are required.

## LITERATURE CITED

- Ackerman, D. and K. Schiff. 2003. Modeling storm water mass emissions to the Southern California Bight. *Journal of Environmental Engineering-ASCE* 129:308-317.
- Ackerman, D. and S.B. Weisberg. 2003. Relationship between rainfall and beach bacterial concentrations on Santa Monica Bay beaches. *Journal of Water and Health* 1:85-89.
- Anderson, D.M., J.M. Burkholder, W.P. Cochlan, P.M. Glibert, C.J. Gobler, C.A. Heil, R.M. Kudela, M.L. Parsons, J.E.J. Rensel, D.W. Townsend, V.L. Trainer and G.A. Vargo. 2008. Harmful algal

- blooms and eutrophication: Examining linkages from selected coastal regions of the United States. *Harmful Algae* 8:39-53.
- Anderson, D.M., P.M. Glibert and J.M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* 25:704-726.
- Bakun, A. 1973. Coastal upwelling indices, west coast of North America, 1946–1971. NOAA Tech. Rep. NMFS SSRF-671. U.S. Department of Commerce. Washington, DC.
- Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* 247:198-201.
- Bakun, A., D.B. Field, A. Redondo-Rodriguez and S.J. Weeks. 2010. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. *Global Change Biology* 16:1213-1228.
- Bakun, A. and C.S. Nelson. 1991. The seasonal cycle of wind-stress curl in subtropical eastern boundary current regions. *Journal of Physical Oceanography* 21:1815-1834.
- Bakun, A. and S.J. Weeks. 2004. Greenhouse gas buildup, sardines, submarine eruptions and the possibility of abrupt degradation of intense marine upwelling ecosystems. *Ecology Letters* 7:1015-1023.
- Banase, K. and D.C. English. 1994. Seasonality of Coastal Zone Color Scanner phytoplankton pigment in the offshore oceans. *Journal of Geophysical Research-Oceans* 99:7323-7345.
- Barber, R.T. and R.L. Smith. 1981. Coastal upwelling ecosystems. pp. 31-68 in: A. R. Longhurst (ed.), *Analysis of Marine Ecosystems*. Academic Press. London, UK.
- Black, B.A., I.D. Schroeder, W.J. Sydeman, S.J. Bograd, B.K. Wells and F.B. Schwing. 2011. Winter and summer upwelling modes and their biological importance in the California Current Ecosystem. *Global Change Biology* 17:2536-2545.
- Bograd, S.J., I.D. Schroeder, N. Sarkar, X. Qiu, W.J. Sydeman and F.B. Schwing. 2009. Phenology of coastal upwelling in the California Current. *Geophysical Research Letters* 36:L01602.
- Boyce, D.G., M.R. Lewis and B. Worm. 2010. Global phytoplankton decline over the past century. *Nature* 466:591-596.
- Bray, N.A., A. Keyes and W.M.L. Morawitz. 1999. The California Current system in the Southern California Bight and the Santa Barbara Channel. *Journal of Geophysical Research-Oceans* 104:7695-7714.
- Campbell, J.W. 1995. The lognormal-distribution as a model for biooptical variability in the sea. *Journal of Geophysical Research-Oceans* 100:13237-13254.
- Cannizzaro, J.P. and K.L. Carder. 2006. Estimating chlorophyll *a* concentrations from remote-sensing reflectance in optically shallow waters. *Remote Sensing of Environment* 101:13-24.
- Caron, D.A. 2008. Collaborative HAB research and toxicity on the San Pedro Shelf. pp. B-3 in, Harmful Algal Bloom Monitoring and Alert Program (HABMAP) Working Group. The regional workshop for harmful algal blooms (HABs) in California coastal waters, Vol. Report #565. Southern California Coastal Water Research Project. Costa Mesa, CA.
- Chavez, F.P., P.G. Strutton, G.E. Friedrich, R.A. Feely, G.C. Feldman, D.G. Foley and M.J. McPhaden. 1999. Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño. *Science* 286:2126-2131.
- Chavez, F.P., P.G. Strutton and M.J. McPhaden. 1998. Biological-physical coupling in the central equatorial Pacific during the onset of the 1997-98 El Niño. *Geophysical Research Letters* 25:3543-3546.
- Chereskin, T.K. and P.P. Niiler. 1994. Circulation in the Ensenada Front - September 1988. *Deep-Sea Research Part I-Oceanographic Research Papers* 41:1251-1287.
- Claustre, H., A. Morel, S.B. Hooker, M. Babin, D. Antoine, K. Oubelkheir, A. Bricaud, K. Leblanc, B. Queguiner and S. Maritorena. 2002. Is desert dust making oligotrophic waters greener? *Geophysical Research Letters* 29:1469.
- Cullen, J.J. and R.W. Eppley. 1981. Chlorophyll maximum layers of the Southern California Bight and possible mechanisms of their formation and maintenance. *Oceanologica Acta* 4:23-32.

- Cullen, J.J., F.M.H. Reid and E. Stewart. 1982. Phytoplankton in the surface and chlorophyll maximum off southern California in August, 1978. *Journal of Plankton Research* 4:665-694.
- Cullen, J.J., E. Stewart, E. Renger, R.W. Eppley and C.D. Winant. 1983. Vertical motion of the thermocline, nitracline and chlorophyll maximum layer in relation to currents on the Southern California Shelf. *Journal of Marine Research* 41:239-262.
- Culliton, T.J., M.A. Warren, T.R. Goodspeed, D.G. Remer, C.M. Blackwell and J.J. McDonough. 1990. Fifty years of population change along the nation's coasts, 1960-2010. Coastal Trends Series, Report No. 2. NOAA Strategic Assessment Branch. Rockville, MD.
- Dall'Olmo, G., A.A. Gitelson, D.C. Rundquist, B. Leavitt, T. Barrow and J.C. Holz. 2005. Assessing the potential of SeaWiFS and MODIS for estimating chlorophyll concentration in turbid productive waters using red and near-infrared bands. *Remote Sensing of Environment* 96:176-187.
- 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. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* 35:L08607.
- Emery, K.O. 1960. The Sea off Southern California. John Wiley and Sons. New York, NY.
- Glibert, P.M., D.M. Anderson, P. Gentien, E. Graneli and K.G. Sellner. 2005. The global complex phenomena of Harmful Algal Blooms. *Oceanography* 18:136-147.
- Glibert, P.M., J. Harrison, C. Heil and S. Seitzinger. 2006. Escalating worldwide use of urea - a global change contributing to coastal eutrophication. *Biogeochemistry* 77:441-463.
- Gordon, H.R. and M. Wang. 1994. Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm. *Applied Optics* 33:443-452.
- Gregg, W.W. (ed.). 2007. Ocean-Colour Data Merging. (Vol. 6). Dartmouth, Canada: IOCCG.
- Gregg, W.W. and N.W. Casey. 2004. Global and regional evaluation of the SeaWiFS chlorophyll data set. *Remote Sensing of Environment* 93:463-479.
- Gregg, W.W., N.W. Casey and C.R. McClain. 2005. Recent trends in global ocean chlorophyll. *Geophysical Research Letters* 32:L03606.
- Haney, R.L., R.A. Hale and D.E. Dietrich. 2001. Offshore propagation of eddy kinetic energy in the California Current. *Journal of Geophysical Research-Oceans* 106:11709-11717.
- Harms, S. and C.D. Winant. 1998. Characteristic patterns of the circulation in the Santa Barbara Channel. *Journal of Geophysical Research-Oceans* 103:3041-3065.
- Haurly, L.R., E.L. Venrick, C.L. Fey, J.A. McGowan and P.P. Niiler. 1993. The Ensenada Front: July 1985. *California Cooperative Oceanic Fisheries Investigations Reports* 34:69-88.
- Hayward, T.L. and E.L. Venrick. 1998. Nearsurface patterns in the California Current: Coupling between physical and biological structure. *Deep-Sea Research II* 45:1617-1638.
- Heisler, J., P.M. Glibert, J.M. Burkholder, D.M. Anderson, W.P. Cochlan, W.C. Dennison, Q. Dortch, C.J. Gobler, C.A. Heil, E. Humphries, A. Lewitus, R.E. Magnien, H.G. Marshall, K.G. Sellner, D.A. Stockwell, D.K. Stoecker and M. Suddleson. 2008. Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae* 8:3-13.
- Henson, S.A., J.L. Sarmiento, J.P. Dunne, L. Bopp, I. Lima, S.C. Doney, J. John and C. Beaulieu. 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* 7:621-640.
- Henson, S.A. and A.C. Thomas. 2007. Interannual variability in timing of bloom initiation in the California Current System. *Journal of Geophysical Research-Oceans* 112.
- Hickey, B.M. 1979. The California Current system: Hypotheses and facts. *Progress in Oceanography* 8:191-279.
- Hickey, B.M., E.L. Dobbins and S.E. Allen. 2003. Local and remote forcing of currents and temperature in the central Southern California Bight. *Journal*

- of *Geophysical Research-Oceans* 108:3081, doi:3010.1029/2000JC000313.
- Holmes, R.W., P.M. Williams and R.W. Eppley. 1967. Red water in La Jolla Bay, 1964-1966. *Limnology and Oceanography* 12:503-512.
- Kahru, M., R.M. Kudela, M. Manzano-Sarabia and B.G. Mitchell. 2009. Trends in primary production in the California Current detected with satellite data. *Journal of Geophysical Research-Oceans* 114:C02004.
- Kahru, M. and B.G. Mitchell. 2008. Ocean color reveal increased blooms in various parts of the world. *EOS* 89:170.
- Ketchum, B.H. 1951. The exchanges of fresh and salt waters in tidal estuaries. *Journal of Marine Research* 10:18-38.
- Kilpatrick, K.A., G.P. Podesta and R. Evans. 2001. Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. *Journal of Geophysical Research-Oceans* 106:9179-9197.
- Lentz, S.J. and C.D. Winant. 1986. Subinertial currents on the southern California shelf. *Journal of Physical Oceanography* 16:1737-1750.
- Longhurst, A.R. 1995. Seasonal cycles of pelagic production and consumption. *Progress in Oceanography* 36:77-167.
- Lynn, R.J., S.J. Bograd, T.K. Chereskin and A. Huyer. 2003. Seasonal renewal of the California Current: The spring transition off California. *Journal of Geophysical Research-Oceans* 108:3279.
- Lynn, R.J. and J.J. Simpson. 1987. The California Current System: The seasonal variability of its physical characteristics. *Journal of Geophysical Research-Oceans* 92:12947-12966.
- Lyon, G.S. and E.D. Stein. 2009. How effective has the Clean Water Act been at reducing pollutant mass emissions to the Southern California Bight over the past 35 years? *Environmental Monitoring and Assessment* 154:413-426.
- Mantyla, A.W., S.J. Bograd and E.L. Venrick. 2008. Patterns and controls of chlorophyll-a and primary productivity cycles in the Southern California Bight. *Journal of Marine Systems* 73:48-60.
- Maritorena, S., A.Y. Morel and B. Gentili. 1994. Diffuse reflectance of oceanic shallow waters: Influence of water depth and bottom albedo. *Limnology and Oceanography* 39:1689-1703.
- McClain, C.R. 2009. A decade of satellite ocean color observations. *Annual Review of Marine Science* 1:19-42.
- Millan-Nunez, R., S. Alvarez-Borrego and C.C. Trees. 1996. Relationship between deep chlorophyll maximum and surface chlorophyll concentration in the California Current system. *California Cooperative Oceanic Fisheries Investigations Reports* 37:241-250.
- Mitarai, S., D.A. Siegel, J.R. Watson, C. Dong and J.C. McWilliams. 2009. Quantifying connectivity in the coastal ocean with application to the Southern California Bight. *Journal of Geophysical Research-Oceans* 114:C10026.
- Moulin, C., H.R. Gordon, R.M. Chomko, V.F. Banzon and R.H. Evans. 2001. Atmospheric correction of ocean color imagery through thick layers of Saharan dust. *Geophysical Research Letters* 28:5-8.
- Muller-Karger, F.E., C. Hu, S. Andrefouet, R. Varela and R.C. Thunell. 2005. The color of the coastal ocean and applications in the solution of research and management problems. pp. 101-127 in: R. L. Miller, C. E. Del Castillo and B. A. McKee (eds.), *Remote Sensing of Coastal Aquatic Environments*. Springer. Dordrecht.
- National Research Council. 2000. *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution*. National Academy Press. Washington, DC.
- Nezlin, N.P., P.M. DiGiacomo, D.W. Diehl, B.H. Jones, S.C. Johnson, M.J. Mengel, K.M. Reifel, J.A. Warrick and M. Wang. 2008. Stormwater plume detection by MODIS imagery in the southern California coastal ocean. *Estuarine, Coastal and Shelf Science* 80:141-152.
- Nezlin, N.P. and B.-L. Li. 2003. Time-series analysis of remote-sensed chlorophyll and environmental factors in the Santa Monica-San Pedro Basin off southern California. *Journal of Marine Systems* 39:185-202.

- Nezlin, N.P. and E.D. Stein. 2005. Spatial and temporal patterns of remotely-sensed and field-measured rainfall in southern California. *Remote Sensing of Environment* 96:228-245.
- Nixon, S.W. 1995. Coastal marine eutrophication: A definition, social causes, and future concerns. *Ophelia* 41:199-219.
- Noble, M.A., H.F. Ryan and P.L. Wiberg. 2002. The dynamics of subtidal poleward flows over a narrow continental shelf, Palos Verdes, CA. *Continental Shelf Research* 22:923-944.
- O'Loughlin, G., W. Huber and B. Chocat. 1996. Rainfall-runoff processes and modelling. *Journal of Hydraulic Research* 34:733-751.
- O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru and C. McClain. 1998. Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research-Oceans* 103:24937-24953.
- Paerl, H.W. 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. *Limnology and Oceanography* 42:1154-1165.
- Paerl, H.W. and J. Huisman. 2008. Blooms like it hot. *Science* 320:57-58.
- Peterson, W.T. and F.B. Schwing. 2003. A new climate regime in northeast Pacific ecosystem. *Geophysical Research Letters* 30:1896.
- Pierce, S.D., J.A. Barth, R.E. Thomas and G.W. Fleischer. 2006. Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress. *Geophysical Research Letters* 33:L22S04.
- Ransibrahmanakul, V. and R.P. Stumpf. 2006. Correcting ocean colour reflectance for absorbing aerosols. *International Journal of Remote Sensing* 27:1759-1774.
- Reid, F.M.H., E. Stewart, R.W. Eppley and D. Goodman. 1978. Spatial distribution of phytoplankton species in chlorophyll maximum layers off southern California. *Limnology and Oceanography* 23:219-226.
- Reid, J.L., Jr. and A.W. Mantyla. 1976. The effect of the geostrophic flow upon coastal sea elevations in the northern North Pacific ocean. *Journal of Geophysical Research* 81:3100-3110.
- Ryan, J.P., J.F.R. Gower, S.A. King, W.P. Bissett, A.M. Fischer, R.M. Kudela, Z. Kolber, F. Mazzillo, E.V. Rienecker and F.P. Chavez. 2008. A coastal ocean extreme bloom incubator. *Geophysical Research Letters* 35:L12602.
- Sandwell, D.T. 1987. Biharmonic spline interpolation of GEOS-3 and SEASAT Altimeter Data. *Geophysical Research Letters* 14:139-142.
- Santer, R. and C. Schmechtig. 2000. Adjacency effects on water surfaces: primary scattering approximation and sensitivity study. *Applied Optics* 39:361-375.
- Schiff, K.C., M.J. Allen, E.Y. Zeng and S.M. Bay. 2000. Southern California. *Marine Pollution Bulletin* 41:76-93.
- Schwing, F.B., N.A. Bond, S.J. Bograd, T. Mitchell, M.A. Alexander and N. Mantua. 2006. Delayed coastal upwelling along the US West Coast in 2005: A historical perspective. *Geophysical Research Letters* 33:L22S01.
- Schwing, F.B. and R. Mendelssohn. 1997. Increased coastal upwelling in the California Current System. *Journal of Geophysical Research-Oceans* 102:3421-3438.
- Schwing, F.B., T. Murphree, L. deWitt and P.M. Green. 2002. The evolution of oceanic and atmospheric anomalies in the northeast Pacific during the El Niño and La Niña events of 1995-2001. *Progress in Oceanography* 54:459-491.
- Sen, P.K. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* 63:1379-1389.
- Strub, P.T., J.S. Allen, A. Huyer and R.L. Smith. 1987a. Large-scale structure of the spring transition in the coastal ocean off western North America. *Journal of Geophysical Research-Oceans* 92:1527-1544.
- Strub, P.T., J.S. Allen, A. Huyer, R.L. Smith and R.C. Beardsley. 1987b. Seasonal cycles of currents, temperatures, winds, and sea level over the northeast

Pacific continental shelf: 35N to 48N. *Journal of Geophysical Research-Oceans* 92:1507-1526.

Strub, P.T. and C. James. 1988. Atmospheric conditions during the spring and fall transition in the coastal ocean off western United States. *Journal of Geophysical Research-Oceans* 93:15561-15584.

Sverdrup, H.U. and R.H. Fleming. 1941. The waters off the coast of southern California, March to July 1937. *Bulletin of the Scripps Institution of Oceanography* 4:261-378.

Thomas, A.C. and P. Brickley. 2006. Satellite measurements of chlorophyll distribution during spring 2005 in the California Current. *Geophysical Research Letters* 33:L22S05.

Thomas, A.C., P. Brickley and R. Weatherbee. 2009. Interannual variability in chlorophyll concentrations in the Humboldt and California Current Systems. *Progress in Oceanography* 83:386-392.

Warrick, J.A., L. Washburn, M.A. Brzezinski and D.A. Siegel. 2005. Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River. *Estuarine, Coastal and Shelf Science* 62:559-574.

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

## ACKNOWLEDGMENTS

The authors would like to thank the SeaWiFS Project (Code 970.2) for the production and distribution of the SeaWiFS data. These activities are sponsored by NASA's Mission to Planet Earth Program. We also thank the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology for SST data and the NOAA National Data Center Climate Data Online (NNDC/CDO) for the rain gauge-measured precipitation data. We thank Doug Pirhalla (NOAA) for help in SeaWiFS data processing. Becky Shaffner helped in processing GIS watershed data. The remarks of Alex Steele and an anonymous reviewer were extremely helpful and significantly improved the paper.