Pergamon

Progress in Oceanography •• (2002) •••–•••

Progress in Oceanography

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Effects of the 1997–98 El Nino on seasonal variations in suspended and sinking particles in the Santa Barbara basin

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Abstract

The relationship between water column processes and sedimentation was investigated using a five year time series of bi-weekly water column measurements and continuous sediment trap collections in the Santa Barbara Basin, California. Conditions during the strong El Niño period of 1997–98 were compared to those during the previous years and the post El Niño period. Suspended particulate concentrations of chlorophyll a (chl a), particulate organic carbon (POC), particulate organic nitrogen (PON) and biogenic silica (bSi) normally underwent a seasonal cycle characterized by high phytoplankton abundance in the spring, dominated by diatoms, followed by lower concentrations of biogenic particles throughout the rest of the year. Maxima in sinking fluxes of POC, PON, bSi and lithogenic silica (lSi) generally occurred during the summer. Prior to the El Niño period, molar ratios of C/N, Si/C and Si/N were all higher in sinking particulate material relative to particulate material suspended in the upper 75 m. Si/N and Si/C ratios were highest in the spring and summer in both surface and sinking pools.

During the 1997–98 El Niño, the seasonal evolution of the density structure of surface waters was altered by the presence of a water mass high in temperature and low in salinity. The depression of the thermocline resulted in concentrations of nitrate, phosphate and silicic acid in the upper 75 m becoming lower that those measured in other years. Mean chl a and bSi concentrations integrated from the surface to 75 m were low on an annual basis, but there were no clear changes in the seasonality of suspended particle concentrations. Perhaps unexpectedly, fluxes of POC, PON and lSi at 470 m increased during the El Niño period. Lower C/N ratios and shorter turnover times suggest increases in the export ratios of POC and PON at that time. We hypothesize that the increase in lSi flux, despite the absence of elevated concentrations of lSi in the upper 75 m, resulted from the lateral advection of particles into the region from the increased riverine discharges at the margins of the basin and subsequent scavenging of the small particles by organic material. Decreases in ratios of C/N, Si/C and Si/N in sinking particles that occurred during the El Niño were sustained until the end of the time series in June 1999, and may have resulted from a shift toward a less diatom dominated pool of sinking particles. © 2002 Published by Elsevier Science Ltd.

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0079-6611/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0079-6611(02)00045-9

1. Introduction

The El Niño mode of the El Niño–Southern Oscillation (ENSO) phenomenon is associated with changes in global climate and anomalous warming in the eastern equatorial Pacific Ocean. During El Niño conditions, dramatic changes in water column structure occur in the productive eastern boundary upwelling regions of North and South America (e.g., Lynn et al., 1998; Guilderson & Schrag, 1998). Associated changes in chemical conditions of the upper water column cascade to the biology. Biological impacts include: (1) Reductions in oxygen consumption rates of microplankton (Eissler & Quiñones, 1999); (2) Reductions in phytoplankton nitrogen uptake rates (Wilkerson, Dugdale, & Barber, 1987); (3) Low gonad production and low annual somatic production per biomass in bivalves (Urban & Tarazona, 1996); (4) A shift towards smaller classes in crustacean zooplankton (González, Sobarzo, Figueroa, & Nöthig, 2000); and (5) Minimum abundances of both macrozooplankton and seabirds (Lynn et al., 1998).

Changes in phytoplankton processes brought on by El Niño can affect global as well as local biogeochemical cycles. For example, a phytoplankton bloom of exceptionally large spatial extent developed in the equatorial Pacific after the 1997–98 El Niño event (Chavez et al., 1999). This bloom was associated with low nutrient and CO_2 concentrations for this region, which is normally the largest oceanic source of CO_2 to the atmosphere. Wilkerson, Dugdale and Barber (1987) documented the dramatic effect of the 1976 El Niño conditions had on nitrate and ammonium concentrations and uptake rates by the phytoplankton assemblage in the Peru upwelling system. They indicated that suppression of N uptake may have been a widespread phenomenon in both the California and Peru upwelling systems. Since nitrate uptake is a measure of new production, which is the maximum amount of material that can be exported from a steady-state system (Dugdale & Goering, 1967), El Niño conditions can clearly have effects on the biological pump, or the ability of biological activity to transport C from the atmosphere to the seafloor.

Diatoms are a common component of the phytoplankton assemblages in coastal upwelling areas (Guillard & Kilham, 1978). Unusual among phytoplankton, diatoms have an obligate requirement for Si, which they use to construct their siliceous cell walls. Thus, potentially the availability of silicon can limit the productivity of the phytoplankton assemblage. In addition, diatom blooms have been observed to flocculate and sink rapidly to the seafloor (Smetacek, 1985; Alldredge & Gotschalk, 1989), potentially transporting large amounts of organic material as well as opaline silica. Despite these potential links between the cycling of Si, C and N, neither the seasonal trends in the coupling between C, N and Si nor the effect of climatic events on this coupling have been described.

The data presented here were collected in the Santa Barbara Basin (SBB), a basin containing sediments of paleoceanographic importance, which clearly record strong El Niño signatures (Lange et al., 1987; Kennedy & Brassell, 1992). Surface conditions in the SBB are influenced by the upwelling off Point Conception at its northwestern margin and the warmer, more saline waters of the Southern California Countercurrent that entering the basin from the south. The center of the basin is ~600 m deep and the sills at its western and eastern boundaries are at 475 and 230 m, respectively. Low-oxygen East Pacific intermediate water bisects the basin between the two sills and is further depleted of oxygen by the decomposition of sedimenting organic material. Despite occasional flushing of the basin (e.g., Sholkovitz & Gieskes, 1971), the sediments are preserved in laminated sequences (review by Schimmelmann & Lange, 1996). These laminae consist mainly of terrigenous detritus and biogenic silica (Grimm, Lange, & Gill, 1996), and form a continuous, high resolution record of recent climatic fluctuations over much of the Holocene (Kennett & Ingram, 1995).

The objective of this study is to document the effects of particularly strong El Niño conditions on the cycling of C, N and Si in surface waters and their consequent effects on vertical export in the Santa Barbara Basin (SBB). The 1997–98 El Niño serendipitously developed during an ongoing long-term study, providing a time series, which depicted biogeochemical cycling under ‘normal’ conditions prior to the evolution of this climatic event. We will first describe the variability inherent in the water column and sedimentation processes between 1994 and 1997, prior to the El Niño conditions. Our dataset is unique because surface measurements have been conducted at the same temporal resolution as particle flux measurements (twice-monthly) over several years. Thus, we will address the relationship between surface processes and sedimentation before, during and after the 1997–98 El Niño at a high resolution.

Past and ongoing interest in the characterization of the physical aspects of the water column and circulation (e.g. Harms & Winant, 1998; Dever & Winant, this issue) and the sedimentary history and processes in the SBB form a well-developed context for the analysis of biological processes in the water column. It has been suggested that variability in signals recorded in the sediments of the SBB may reflect climate changes over larger scales (Behl & Kennett, 1996; Berger & Lange, 1998; Lange, Burke, & Berger, 1990). An implicit assumption of these studies, which we will test, is that climatic conditions affects export processes in this basin.

2. Methods

2.1. Station locations

Physical, chemical and biological properties were measured twice monthly in the vicinity of a station 20 km offshore in the Santa Barbara Basin (SBB). Sampling of the upper 75 m of the water column was carried out at 34°17′30″ N, 120°00′30″W before June 1995. After June 1995, when a subsurface sediment-trap mooring was deployed 10 km to the southeast at 34°15′00″N, 119°54′30″W, the water column sampling was shifted to this new location (Fig. 1). Sediment trap and water column collections were continued until August 1999. The water masses at the two water column stations were biologically similar; the chlorophyll a concentrations (level 2 SeaWiFS data) at the two sites were indistinguishable (Shipe & Brzezinski, 2000). In order to assess cross-channel variability, surface samples were also collected along a 7–station transect at stations located 3, 9, 14, 20, 26, 32 and 43 km offshore (Fig. 1).

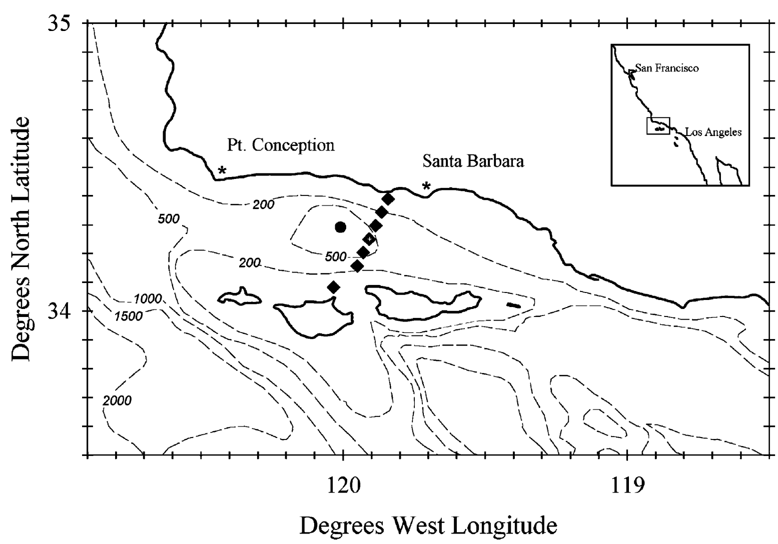

Fig. 1. Sampling stations and bathymetry of the Santa Barbara Basin. The seven cross-channel stations are indicated by diamonds, and are sequentially numbered (1–7) from the mainland to the Channel Islands. The sampling site before June 1995 (34°17′30″N, 120°00′30″W) is indicated by a circle the sampling site after June 1995 is indicated by a diamond with a cross-hair (station 4 and subsurface mooring site; 34°15′00″N, 119°54′30″W). The small box in the inset map indicates the area portrayed in the larger map.

2.2. Upper water column sampling

Water samples were collected at seven discrete depths (0, 5, 10, 20, 30, 50 and 75 m) for particulate and nutrient analyses. Prior to August 1997, samples were collected using a 10L Niskin bottle and were drained into darkened 20L carboys. These carboys were transported to the laboratory within an hour in insulated containers and were inverted several times to resuspend any material that had settled before draining subsamples. After August 1997 the water samples were collected using a Seabird compact rosette with 5L Niskin bottles and all filtrations were done at sea. Throughout the time series, approximately 30 ml of sample water was filtered through 0.2 μm filters before being frozen in small vials for nutrient analyses. Nitrate and phosphate concentrations were determined using a Zelweger Analytics, Inc. flow injection analyzer, model QuikChem 8000, resulting in precisions of ±0.1 μM and ±0.05 μM (or 5%) for nitrate and phosphate concentrations, respectively. Determinations of particulate organic carbon (POC) and particulate organic nitrogen (PON) were performed as described by Sharp (1992) using a CHN analyzer (Leeman Labs Inc., CE Model 440) on three replicate 500 ml samples filtered onto combusted GF/F filters (Whatman brand). POC and PON concentrations were not measured at the six lower depths after August 1997, and only surface concentrations were measured between August 1997 and October 1998. Two replicate 200 ml samples were filtered onto GF/F filters and chlorophyll a (chl a) concentrations were determined using a Turner Model 111 fluorometer according to the technique of Parsons, Maita and Lalli (1984). Dissolved silicon, biogenic silica and lithogenic silica concentrations were measured as described by Shipe and Brzezinski (2000).

After August 1996, a Sea-Bird Electronics 911plus CTD was deployed with a Sea-Tech 660 nm beam transmissometer on a SBE 32C compact carousel with the intent of sampling to within 5 m of the bottom at each station. We report temperature and beam attenuation during the downcast.

The temporal resolution of sampling was lower during the El Niño period because of the poor weather conditions and equipment failures. It was only possible to profile the water column properties at the mooring site (station 4) on four dates between September 1997 and March 1998. However, surface measurements at the seven cross-channel stations were collected on these four dates, and also on 2 March 1998.

2.3. Sediment trap samples

A Mark 7GW-13 PARFLUX rotating time-series sediment trap (McLane Research Laboratories, Inc.) with 12 500 ml collecting bottles was deployed at the mooring site (34°15′00″N, 119°54′30″W) at a depth of 470 m, approximately 50 m above the seafloor, as previously described by Passow et al. (2002) and Shipe and Brzezinski (2000). The collecting bottles were filled with brine solution poisoned with 4% formalin, and a new bottle rotated into the collection position every two weeks. Between January and June 1999, the frequency of sampling was increased to every week. The sediment trap was serviced every six months. Upon retrieval the pH of the samples was adjusted to 8.0 and the fixative concentration to 4%, and refrigerated at ~4°C. Each sample was divided into 16ths in a rotary plankton splitter using distilled water for rinses. One 1/16th split was picked for swimmers under a dissecting microscope before being passed through a 1 mm Nitex screen. This material was diluted to 250 ml with distilled water and six 20 ml aliquots were removed by pipette while mixing. Each aliquot was filtered onto combusted GF/F filters, and three of them were decalcified with 8N HCL. The filters were dried at 60°C and particulate C and N contents were measured using an automated organic elemental analyzer (Dumas combustion method). A separate 1/16th split was used to determine the biogenic and lithogenic silica concentrations, which were subsequently corrected assuming that the dissolution of lithogenic silica during alkaline digestion led to a factor of 1.6 increase in the biogenic silica concentration as discussed by Shipe and Brzezinski (2000). As a result of this correction, the biogenic silica fluxes reported here should be considered lower estimates.

3. Results

3.1. Physical setting

The surface waters of the SBB consist of a seasonally varying combination of cool waters upwelled offshore of Point Conception and warmer, more saline waters advected in by the Southern California Countercurrent. The contributions of the two water masses vary seasonally in response to local wind stress and basin-scale pressure gradients (Harms & Winant, 1998). Changes in local circulation and water masses occur on the order of days in the SBB. For example, Harms and Winant (1998) show that four distinct states of circulation are traversed approximately every 16 days during the summer and fall. Thus, we suspect there is a great deal of temporal variability in both water column and deep-basin processes that may lead to series of discrete sedimentary events in the upper 75 m of the water column that will not have been discriminated in the sediment trap flux measurements at 470 m.

Time series of temperature, salinity and density from the surface to 75 m at the mooring site during the 1997–98 El Niño show there were dramatic changes in the physical structure of the water column (Shipe & Brzezinski, 2000). There was an abrupt decrease in density throughout the upper 75 m in early June 1997, and an unusually low density and low salinity water mass remained in the channel until the spring of 1998. The extent of the warming of the upper water column and the depression of the thermocline is exemplified by the depth of the 10°C isotherm, which plunged from <100 m and remained >140 m from August 1997 through April 1998 (Fig. 2a). Dever and Winant (this issue) report temperature anomalies at the western and eastern entrances to the SBB of up to +4°C in two pulses. The first pulse occurred in the upper 50 m in May and June, 1997, and the second, stronger and deeper pulse occurred from the end of September 1997 to February 1998.

In the SBB, the relatively weak El Niño conditions in the equatorial Pacific in the winter of 1994–95 (McPhaden, Kessler, & Soreide, 2000) were accompanied by a brief period (November 1994–March, 1995) of low density as a result of low salinities and high temperatures (>13°C to 70 m depth) in the upper 75 m of the water column (data presented by Shipe & Brzezinski, 2000). However, these anomalies were neither as large, nor as prolonged, as those observed during 1997–98, which was one of the most intense and prolonged El Niño events that have been observed in the past ~120 years (Wolter & Timlin, 1988).

3.2. Nutrient concentrations

Nutrient levels during the 1997–98 El Niño were unusually low (Fig. 3). Nitrate concentrations from the surface to 75 m depth at the mooring station fell to <2.0 μM during November 1997. Normally under non El Niño conditions nitrate concentrations at 50–75 m water depths during late fall/early winter range between 10 and 20 μM. Whereas during the El Niño between October 1997 and January 1998 dissolved silicon and phosphate concentrations in the upper 75 m both fell to <5 μM and <0.45 μM, respectively.

Inspection of contour plots of nutrient concentrations over time and latitude suggest that events across the channel were observable at the mooring site in nearly every instance (Fig. 4). However, during spring and summer when nutrient concentrations are normally high, the highest surface concentrations were at times localized, either at offshore stations (e.g. April 1997 and May, 1999), or onshore stations (spring 1998) or in the center of the basin (May, 1998). In a more rigorous analysis, correlation coefficients were calculated between surface nutrient concentrations at the mooring site (station 4) and those at the other six cross-channel stations (Table 1). Statistically significant correlations existed between nitrate and dissolved silicon concentrations at Station 4 and at all the other stations except at the innermost station (station 1). Phosphate concentrations at station 4 were only significantly correlated with the concentrations at the onshore stations 5, 6 and 7. This analysis suggests that nutrient concentrations at the mooring site are fairly

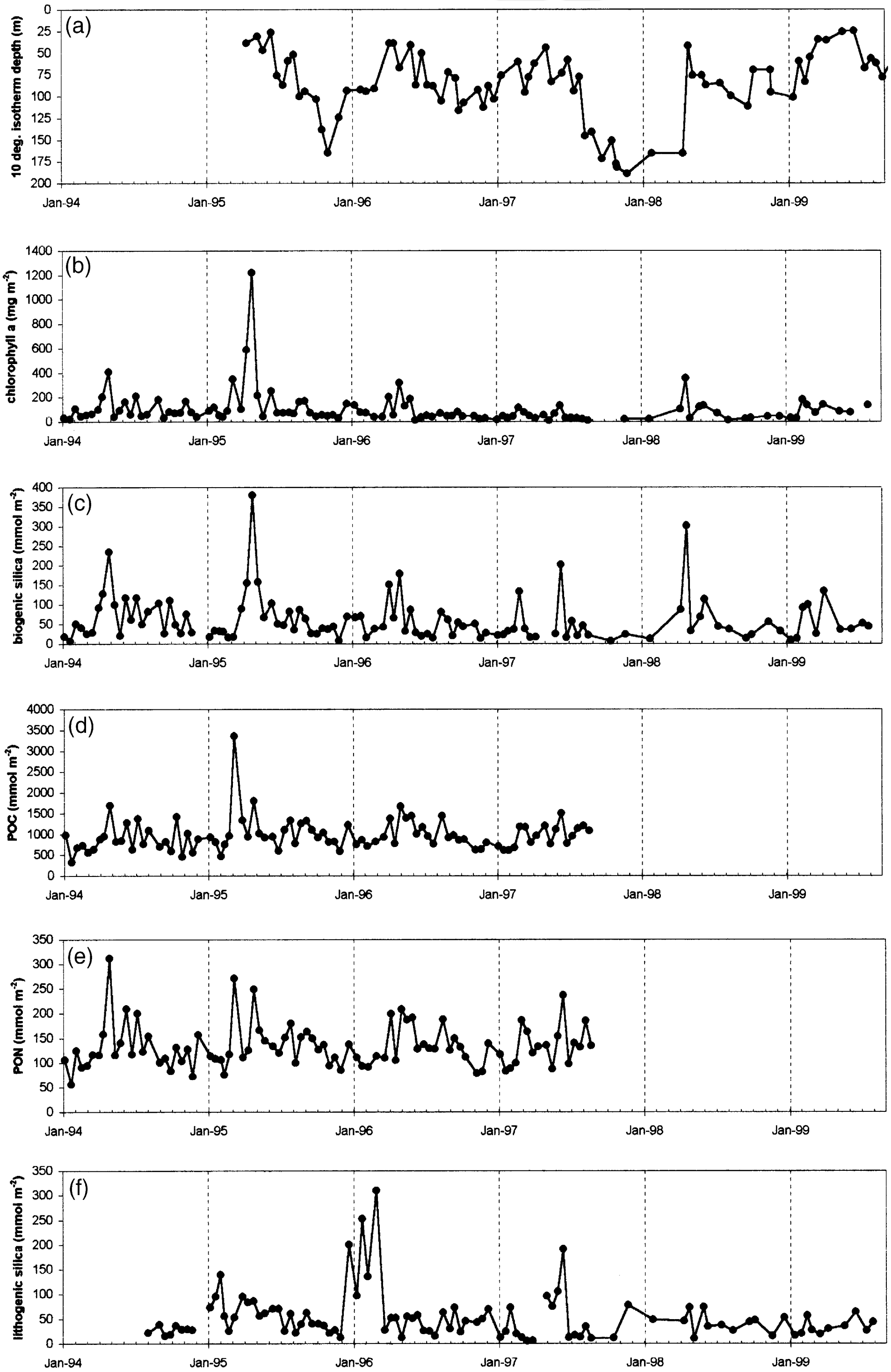

Fig. 2. Time series of (a) the 10°C isotherm depth and concentrations of (b) chlorophyll a (c) biogenic silica (d) particulate organic carbon (POC) (e) particulate organic nitrogen (PON) and (f) lithogenic silica at the mooring station in the SBB, integrated from the surface to 75 m water depth.

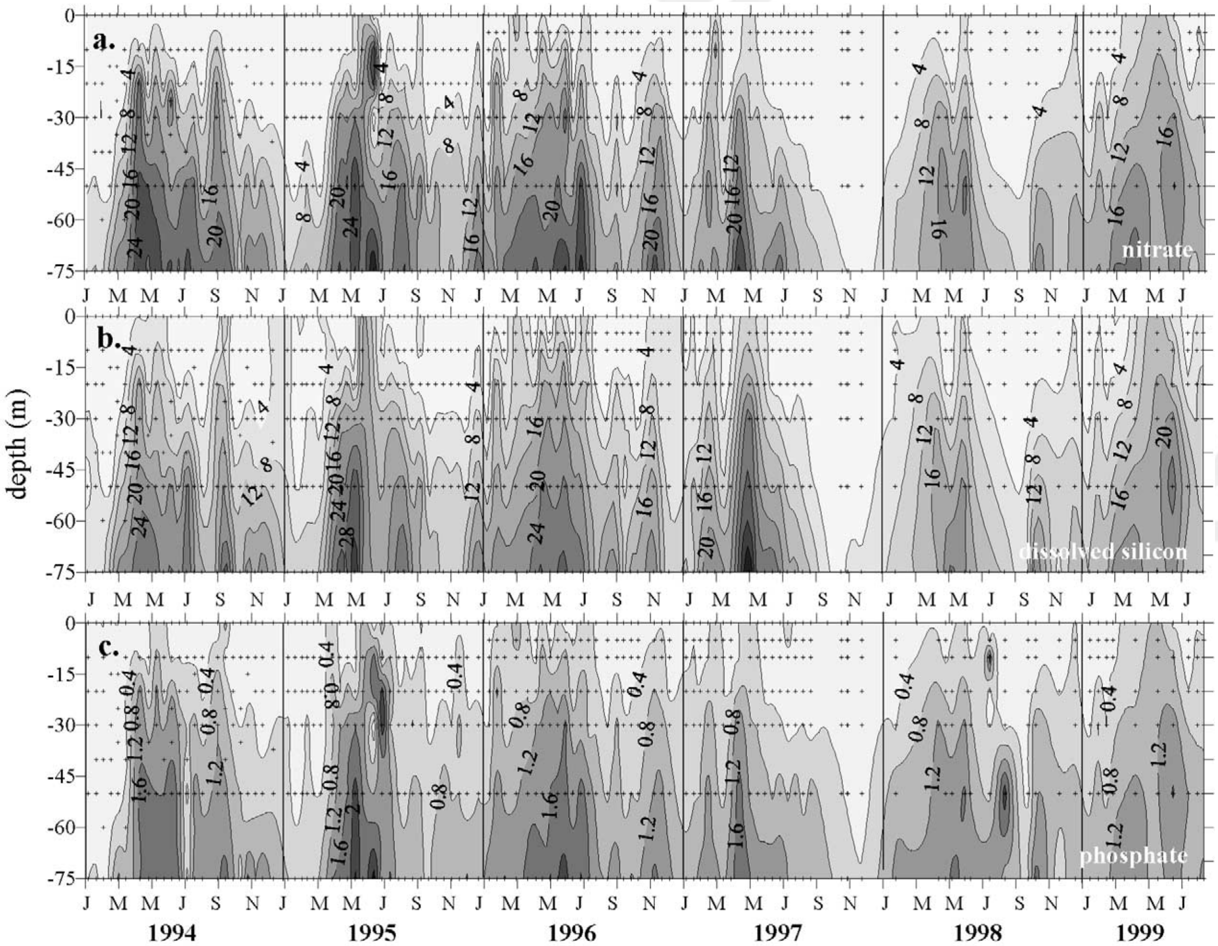

Fig. 3. Time series contour plots of (a) nitrate concentrations (μM) (b) dissolved silicon concentrations (μM) and (c) phosphate concentrations (μM) from the surface to 75 m water depth at the mooring station in the SBB.

representative of those present across the channel, but that inshore nutrient concentrations are somewhat variable.

3.3. Suspended particle concentrations

The seasonal cycles of particulate organic nitrogen (PON), particulate organic carbon (POC), chlorophyll a (chl a) and biogenic silica (bSi) concentrations were each characterized by maxima in late spring each year with smaller pulses occurring throughout the rest of the year (Fig. 2). During the 1997–98 El Niño, chl a concentrations in the upper 75 m underwent their typical annual cycle, but the peak concentrations were the lowest we observed (Fig. 2b). The maximum integrated concentration of chl a during the El Niño was 134 mg m^{-2}, compared to the maxima of 319–1220 mg m^{-2} observed in 1994–1996. At the surface chl a concentrations were fairly similar at the seven cross-channel stations. Most of the maxima observed at the mooring site (20 km offshore) were accompanied by high concentrations across the channel (data not shown). Despite low chl a concentrations observed during the 1997–98 El Niño conditions, neither the

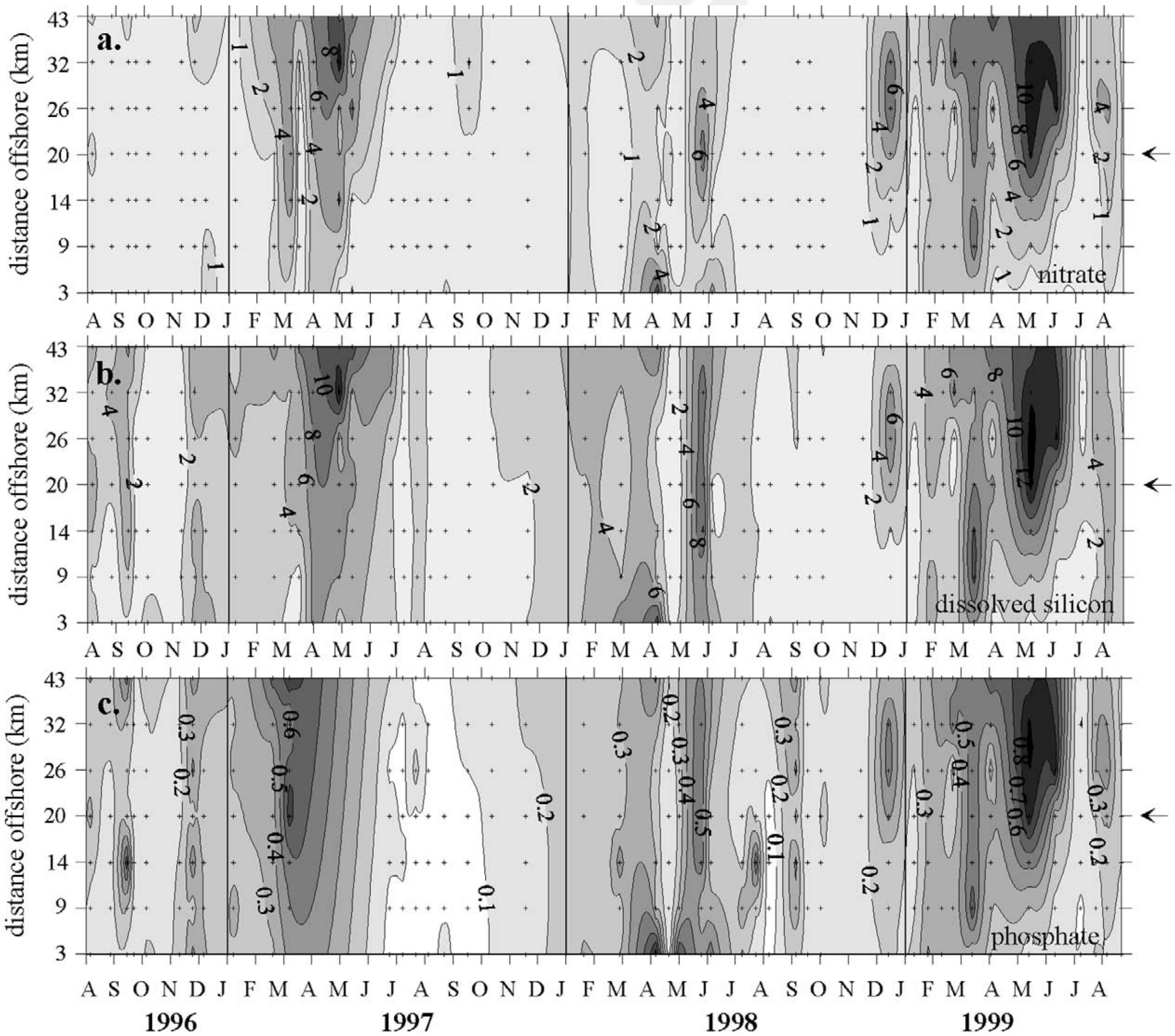

Fig. 4. Time series contour plots of surface (a) nitrate concentrations (μM) (b) dissolved silicon concentrations (μM) and (c) phosphate concentrations (μM) at 7 transect stations across the Santa Barbara Channel.

seasonality of spring maxima nor the maximum concentrations of bSi clearly altered during that time (Fig. 2c).

Although POC and PON concentrations were not measured at subsurface depths after August 1997, surface concentrations at the mooring site indicated there were consistently low values through out the fall and winter of 1997–98. Maximum surface concentrations of POC and PON during that period were 44 and 5.5 μmol l^{-1}, respectively, as compared to 76–310 μmol POC l^{-1} and 8.7–14 μmol PON l^{-1} in the previous years. Surface data have to be interpreted with some caution given that there is a poor relationship between surface and integrated concentrations of POC, PON and chl a. Regressions between the concentrations at the surface and those integrated to 75 m produce r^2 values of 0.36, 0.49 and 0.51 for POC, PON and chl a, respectively. Thus, despite low surface concentrations after August 1997, we cannot rule out the possibility of subsurface maxima. Although no measurements of POC or PON were made during

Table 1
Correlation coefficients for surface nutrient and particulate silicon concentrations between the mooring site (station 4) and each of the cross-channel stations. Autocorrelations were performed for each time series with two week lags in order to determine decorrelation time scales and the appropriate degrees of freedom for the correlation analysis. The statistical significance of correlation coefficients was determined at α=0.05, using both a conservative test for significance in which the decorrelation time is taken as the number of lags before which the correlation coefficient went to zero (+ denotes significance) and a less conservative test for significance, in which the decorrelation time is taken as the number of lags before which the correlation coefficient dropped to the e-folding time (∗ denotes significance). Concentrations at station 4 are perfectly correlated with themselves, hence a correlation coefficient of 1.0 for all parameters

Station	Distance offshore (km)	nitrate	silicate	phosphate	biogenic silica	lithogenic silica
1	3	0.29	0.34	0.20	0.66∗+	0.22
2	9	0.53∗	0.56∗	0.61	0.66∗+	0.31
3	14	0.83∗+	0.83∗+	0.47	0.79∗+	0.56∗
4	20	1.0∗+	1.0∗+	1.0∗+	1.0∗+	1.0∗+
5	26	0.69∗	0.67∗	0.71∗	0.94∗+	0.73∗
6	32	0.74∗	0.75∗	0.82∗+	0.84∗+	0.56∗
7	43	0.76∗	0.74∗	0.80∗	0.55∗	0.28

the post El Niño period, an integrated chl concentration of 357 mg m^{-2} was observed on 10 April 1998 (Fig. 2b). Biogenic silica concentrations of 302 mmol m^{-2} indicate that siliceous organisms were abundant during this bloom (Fig. 2c).

The annual cycle of lithogenic silica (lSi) suspended in the upper 75 m was also altered during the El Niño (Fig. 2f). The annual winter maxima we measured in 1994–1995 and 1995–1996 were 140 and 310 mmol m^{-2} respectively. The annual maximum measured in 1997 was not unusual in magnitude (192 mmol m^{-2}), but was delayed until June. In addition, there was no clear maximum at the mooring station in the winter of 1997–1998, during the El Niño. Although sampling was sparse in winter 1997–98, the observed concentrations of lSi remained consistently <80 mmol m^{-2} after the El Niño until the time series ended in August 1999.

Surface bSi concentrations at the mooring site were highly correlated with those at all of the cross-channel stations. Surface lSi concentrations were only significantly correlated with those at stations 3, 5, 6 and 7 (Table 1). This is probably because lithogenic material of terrestrial origin derived from the plumes of riverine discharges was sinking out of surface waters in nearshore waters (see Warrick et al., 2000; Shipe & Brzezinski, 2000). It was not possible to undertake a similar analysis of the surface concentrations of POC and PON because of the limited number of observations.

Peaks in beam attenuation at a wavelength of 660 nm occurred at many of the stations on several occasions throughout the year. Representative examples of profiles of beam attenuation show maxima occurred at ~180–260 in January 1997, ~70–100 m in August 1999 and ~90–105 m in September 1997 (Fig. 5). These maxima indicate the presence of increased concentrations of particulate material at depth, but since they were not associated with maxima in fluorescence (data not shown), these particles were unlikely to be of biogenic origin, since rapidly sinking aggregates normally contain chlorophyll (Alldredge & Gotschalk, 1990).

The C/N ratio of suspended particulate material in the upper 75 m varied between 4.5 and 12.3, with a mean and standard deviation of 7.3±1.4 (Fig. 6, Table 2). A mean C/N ratio of 7.3 is slightly enriched in carbon relative to 6.6, the Redfield ratio for marine plankton (Table 1) (Redfield, Ketchum & Richards, 1963). This enrichment of C over expected values for living plankton is partially a result of our methodology, which included carbonate from calcified plankton in POC concentrations. There may also be a detrital component to the suspended organic material. The mean suspended C/N ratio implies that the

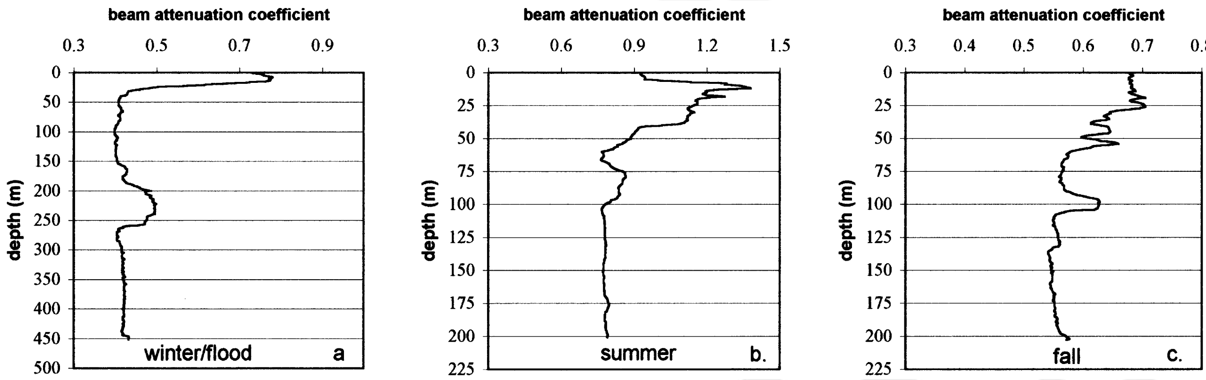

Fig. 5. Vertical profiles of beam attenuation coefficients (m^{-1}) with depth during (a) winter/flood conditions in January 1997 at station 4 (b) summer non-flood conditions in August 1999 at station 4 and (c) fall non-flood conditions in September 1997 at station 6. Beam attenuation coefficients (c) are from the equation: % transmission=$e^{(c*pathlength)}$.

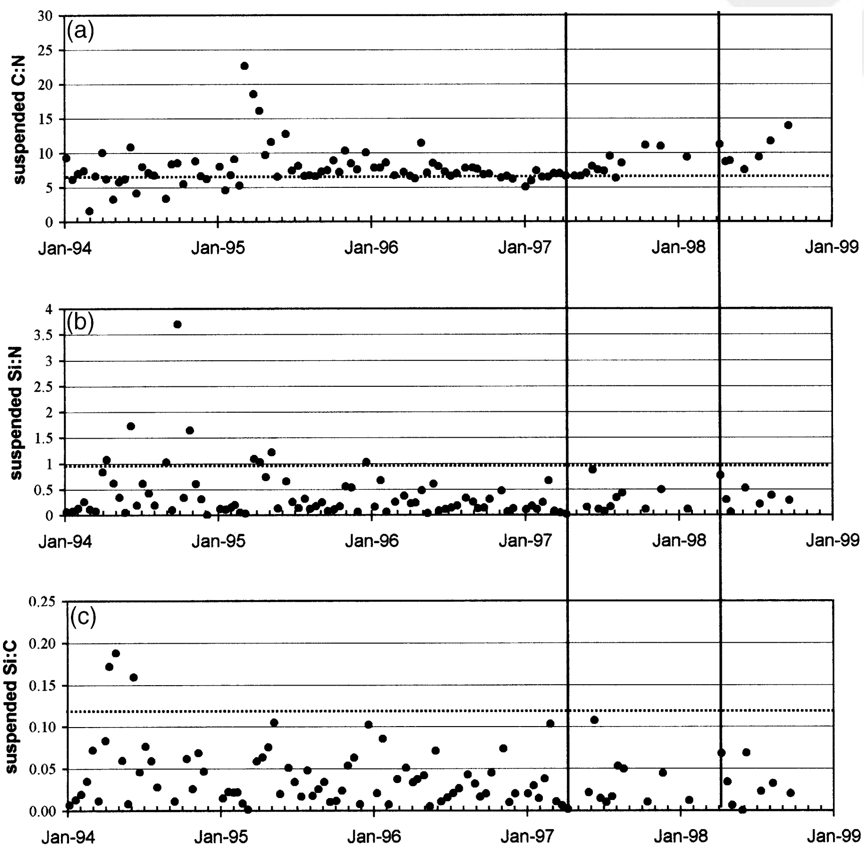

Fig. 6. Time series of elemental ratios of suspended particulate organic carbon, particulate organic nitrogen and biogenic silica. Concentrations were integrated from the surface to 75 m water depth and subsequently divided to provide (a) C/N, (b) Si/N and (c) Si/C ratios. Dashed lines indicate the expected ratios for plankton (Redfield, Ketchum & Richards, 1963) and diatoms (Brzezinski, 1985); C/N=6.6, Si/N=0.95, Si/C=0.12.

Table 2
Elemental ratios of carbon, nitrogen and silicon in the Santa Barbara Basin. Expected ratios of C/N are from Redfield, Ketchum and Richards (1963) and ratios including Si are mean values for diatoms in laboratory culture (Brzezinski, 1985). Mean ratios and standard deviations are given for suspended particulates integrated over the upper 75 m and sinking particulates collected in a sediment trap at 470 m. Ratios for sinking particulates are further divided into ratios before, during and after the 1997–98 El Niño. Since bSi fluxes are minimum estimates (see methods), all sinking Si/N and Si/ratios are also minimum estimates. The number of observations is given in parentheses

	C/N	Si/N	Si/C
Expected	6.6	0.95	0.12
Suspended particles	7.3±1.4 (88)	0.43±0.29 (85)	0.06±0.04 (85)
Sinking particles	8.9±1.6 (89)	3.2±2.0 (89)	0.36±0.21 (89)
pre-El Niño	10.3±0.7 (41)	4.3±2.3 (41)	0.43±0.24 (41)
El Niño	10.0±0.9 (9)	1.7±0.7 (9)	0.17±0.08 (9)
La Niña	7.3±0.8 (39)	2.4±1.0 (39)	0.33±0.14 (39)

maximum contribution of carbonate to our POC concentrations would be only 10%, averaged over the time series. There was greater variability in C/N ratios during the winter of 1994–95 and the following spring, but no seasonal trends were apparent. Although the Si/N and Si/C ratios of the suspended material did not show strong seasonal trends, they did approach or even exceeded those of diatoms grown in laboratory culture (Si/N=0.95, Si/C=0.12; Brzezinski, 1985) both during late spring of each year, and in the fall of 1994 (Fig. 5).

Ratios of C/N, Si/N and Si/C in surface particulates (Fig. 7) are included in addition to the integrated ratios because surface measurements were continued throughout the El Niño period, ending in September 1998. Surface ratios and integrated ratios exhibit similar trends, although C/N ratios tended to be >6.6, and a few values were >15 in the spring of 1995. During and after the El Niño, surface ratios of C/N increased slightly but surface Si/N and Si/C ratios were generally low.

3.4. Sinking particulate flux

Prior to the 1997–98 El Niño, the sinking fluxes of POC, PON, bSi and lSi at 470 m water depth were highest during spring and summer, whereas the flux of $CaCO_3$ was highest in the summer and fall (Fig. 8). The highest sinking fluxes of POC, PON and lSi were observed in the summer of 1997 and early in 1998 during the 1997–98 El Niño. Maximum fluxes of POC, PON and lSi occurred simultaneously, between 31 January 1998 and 4 February 1998, reaching concentrations of 24, 2.5 and 61 mmol m^{-2} d^{-1}, respectively. Despite the high fluxes of organic and inorganic material during the El Niño period, the sinking fluxes of bSi were consistently low with values <9.0 mmol m^{-2} d^{-1} throughout 1997 and 1998. $CaCO_3$ fluxes fluctuated around the time series mean of 2.2 mmol m^{-2} d^{-1}. There are gaps of 89, 175 and 77 days in the observational time series during 1997 and 1998 as a result of clogging of the collecting cone in March 1997, a mechanical failure in August 1997 and again in May 1998, clogging of the trap, this time by an excess of material.

The 1997–98 El Niño conditions were accompanied by changes in the ratios of C, N and Si in sinking particles. The mean ratio of C/N of sinking particles during the entire time series was 8.9±1.6 (Table 2). However, there was a significant decrease in the C/N ratios between the pre-El Niño period and the La Niña period (*t*-test: α=0.95, p=<0.01). The mean C/N ratio was 10.3 prior to April 1997, 10.0 during the El Niño conditions (April 1997–March, 1998) and 7.3 after March 1998 (Fig. 9, Table 2). The flux of Si relative to C and N was also altered during the 1997–98 El Niño (Table 2, Fig. 9). The seasonal cycles of Si/N and Si/C ratios in the sinking particulate material were similar prior to the El Niño, with highest

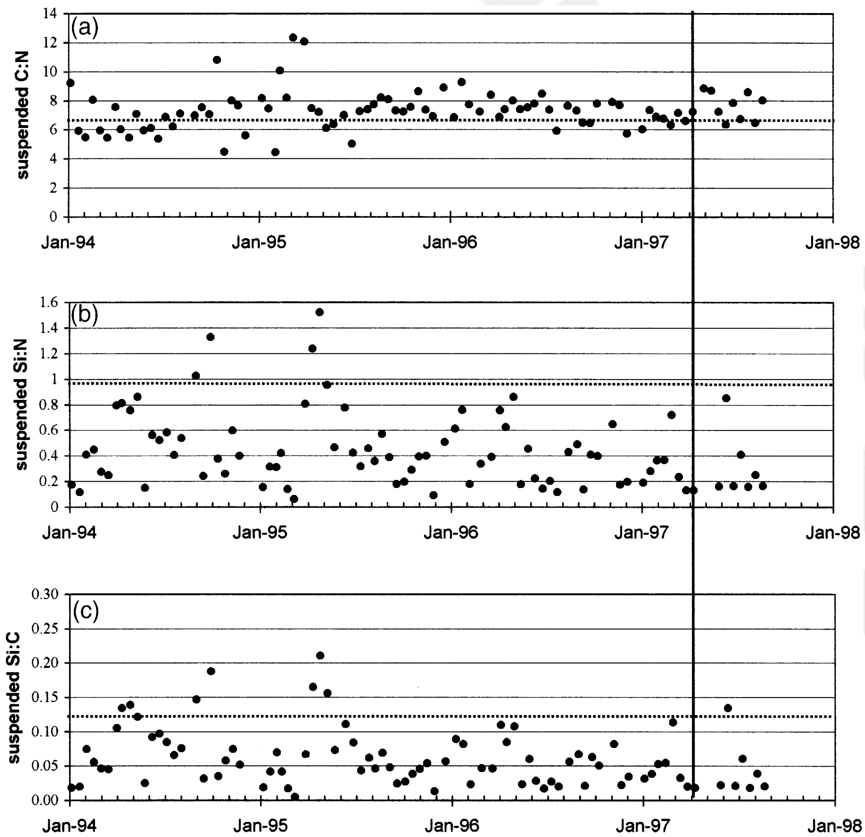

Fig. 7. Time series of elemental ratios of (a) C/N, (b) Si/N and (c) Si/C in suspended particulate material at the surface. Dashed lines indicate the expected ratios for plankton (Redfield, Ketchum & Richards, 1963) and diatoms (Brzezinski, 1985); C/N=6.6, Si/N=0.95, Si/C=0.12.

values in the spring/summer and the lowest values in the winters. The mean values of the Si/N and Si/C ratios of the trap material for the entire time series were 3.2 and 0.36, respectively. The expected ratios for live diatoms (Si/N=0.95 and Si/C=0.12) indicate that these samples were enriched in Si over C and N by a factor of ~3. During the El Niño, mean ratios of Si/N and Si/C were 1.7 and 0.17, respectively, consistently lower than the long-term mean and more similar to those of live diatoms. Post El Niño ratios did not recover to the same magnitude as pre-El Niño values.

4. Discussion

4.1. Typical seasonal cycle of suspended particles

Prior to the 1997–98 El Niño, the Santa Barbara Basin was characterized by a clear seasonal cycle in concentration of suspended particulate material, with the highest concentration of biogenic particles occurring in the spring of each year (Fig. 2). The likely dominance of diatoms was indicated by the association of most of the chl a, POC and PON maxima with high bSi concentrations. The presence of a diatom dominated planktonic assemblage in the Santa Barbara Channel was demonstrated by Venrick (1998).

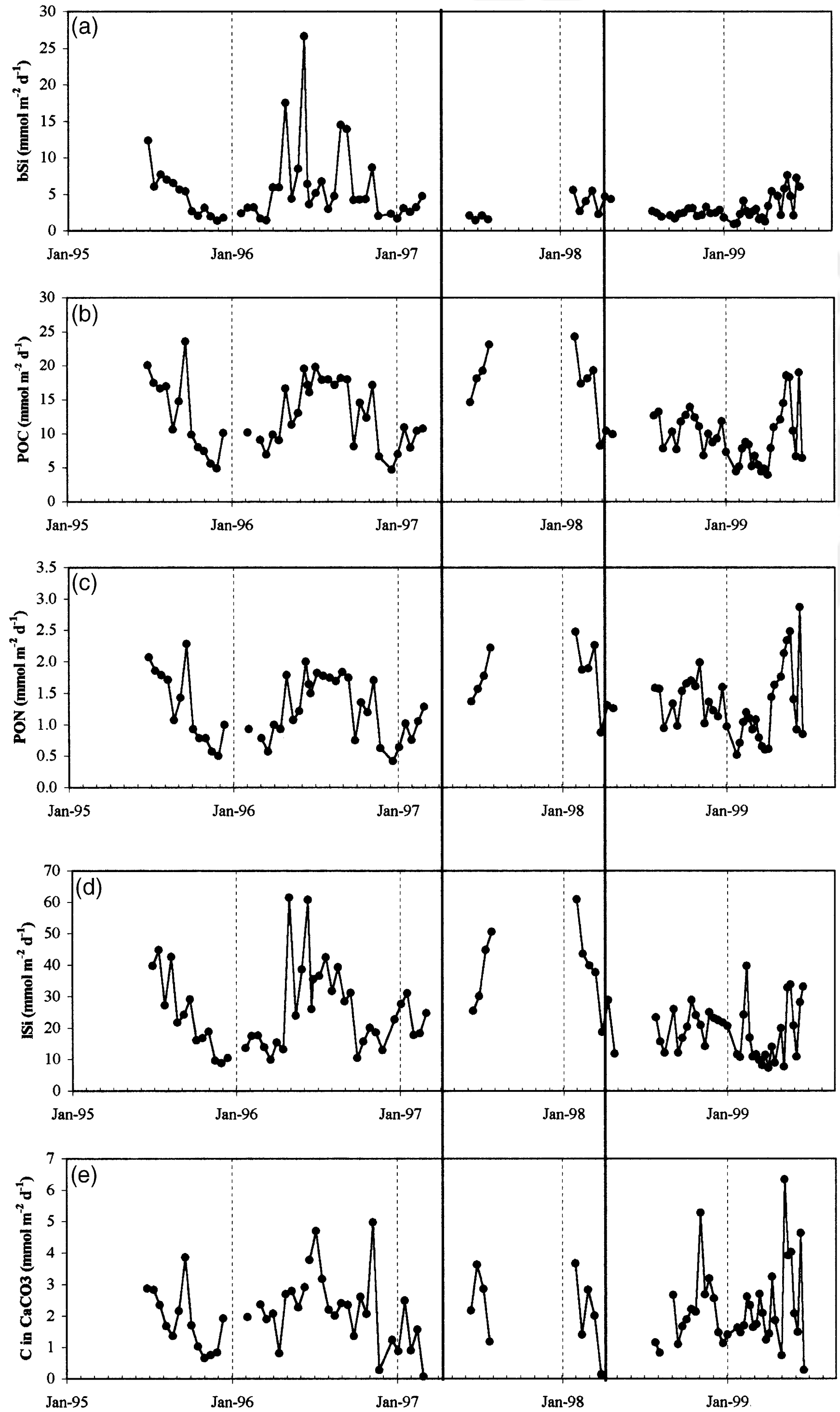

Fig. 8. Time series of flux of (a) biogenic silica (b) POC (c.) PON (d) lithogenic silica and (e) C in $CaCO_3$ into a sediment trap at 470 m located at station 4 in the Santa Barbara Basin. Points are plotted on the date that the trap began collecting.

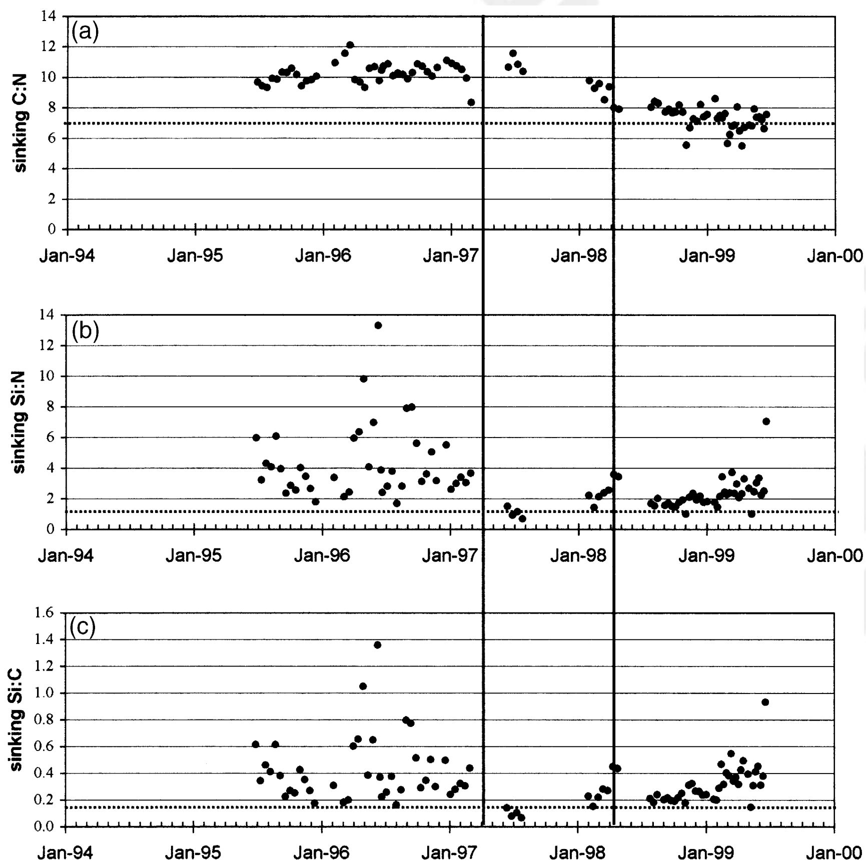

Fig. 9. Time series of elemental ratios of (a) C/N, (b) Si/N and (c) Si/C in particulate material sinking into a trap at 470 m in the Santa Barbara Basin. Dashed lines indicate the expected ratios for plankton (Redfield, Ketchum & Richards, 1963) and diatoms (Brzezinski, 1985); C/N=6.6, Si/N=0.95, Si/C=0.12.

Microscope counts of phytoplankton sampled during the seasonal chlorophyll maximum in 1995 and 1996 revealed that the assemblages were either dominated by *Chaetoceros sp*. or consisted of mixed diatom assemblage (Passow, Shipe, Pak, Brzezinski, & Alldredge, 2000).

The summation of all of the biological processes (including nutrient uptake and the recycling and grazing of particulate material) affecting the C/N ratios of suspended particles resulted in the rations being consistent throughout the time series. The ratios of Si/N and Si/C in the suspended particulate material peaked in the springs of 1994, 1995 and 1996 (Fig. 6), and there were concomitant high concentrations of biogenic silica (Fig. 2) many of which were diatom-derived (Passow, Shipe, Pak, Brzezinski & Alldredge, 2000). Based on past studies of the siliceous phytoplankton flora of the SBB (Lange, Weinheimer, Reid, & Thunell, 1997; Venrick, 1998), we have assumed that the bulk of the biogenic silica is in the form of diatom frustules. High Si/N and Si/C ratios suggest that diatoms dominated the suspended particulate material. However, observations of Si/N and Si/C ratios exceeding 0.95 and 0.12, respectively, indicated that there was probably a detrital component to the bSi on two occasions in the fall of 1994 (31 August and 28 September). Mean ratios of Si/N and Si/C for the entire time series were 0.43 and 0.06, respectively (Table 2). Thus, healthy diatoms could have contributed a maximum of approximately half of the POC and PON, by atoms.

Prior to the 1997–98 El Niño, maximum concentrations of suspended lithogenic silica (lSi) occurred in the late winter (Fig. 2f). This timing is consistent with the observations of Gorsline et al. (1984) who established that the coastal watersheds of the California Borderland deposit terrigenous material during winter runoff events. More specifically, the winter lSi maxima are consistent with the timing of the runoff from the Santa Clara River, which provides the majority of recent sediments accumulating in the SBB (Fleischer, 1972).

4.2. Typical seasonal cycle of sinking particle fluxes

The sinking flux of particulate material in the SBB is highly seasonal, with the highest fluxes of all measured components occurring in the spring and summer and the lowest fluxes occurring in the winter (Fig. 8). We did not detect any distinct surface events being transmitted to depth, probably because the time scales of such events in the surface waters are less than a week, so would not be picked up by the trap sampling, which was twice monthly. However, seasonality in sinking fluxes is related to the seasonal appearance of particles in the euphotic zone. Prior to the El Niño of 1997–98, there were no seasonal variations in sinking C/N ratios. The mean sinking C/N ratio, 10.3, was higher relative to the mean suspended C/N (7.3). There is a higher rate of remineralization of N relative to C, assuming that either the biogenic particles observed in surface waters are the same as those that sink within the basin, or that were additions of small amounts of terrestrially derived material, which would have a higher C/N ratio, or some combination of the two processes.

The seasonal cycles of Si/N and Si/C ratios in the sinking particulate material were similar. The highest values occurred in the spring and summer of 1996 and the lowest values in the winters of 1995–96 and 1996–97. On average, the sinking ratios were seven and six times higher than mean suspended ratios of Si/N and Si/C, respectively indicating the preferential recycling of organic matter over silica below 75 m. However, in April and June 1996 the highest Si/N and Si/C ratios were >40 and >30 times greater than suspended Si/N and Si/C ratios, respectively.

The sinking flux of both organic and inorganic material in the SBB appears to have been driven at least in part by the presence of transparent exopolymer particles (TEP) (Passow, Shipe, Pak, Brzezinski & Alldredge, 2000). They conclude that TEP appears to be required for the export of bSi through the formation of marine snow. Although the relationship between the fluxes of POC and TEP is not as strong as that between bSi and TEP, TEP will also drive the flux of POC at times. The sinking flux of lSi may result from the scavenging of these small particles from the water column onto marine snow although the source of the lSi varies between direct riverine inputs in the spring and resuspended material in the summer.

Thunell (1998) reported sinking fluxes during a three year period between August 1993 and August 1996 into a trap identical to ours, which was also located in the SBB (34°14.033′N, 120°02.856′W). Direct comparisons of the fluxes measured by our trap at 470 m depth and Thunell’s trap at 540 m during June 1995–August 1996 indicate that our trap tended to collect higher quantities of opal, POC, and $CaCO_3$, especially during periods of high sedimentation in the spring and summer of 1996. The seasonal periodicity of the fluxes of organic carbon and biogenic silica we observed agrees with Thunell’s (1998) who also reported minima in sinking fluxes during the autumn and winter, but maxima in fluxes of lithogenic material in late fall/early winter and spring.

Differences in magnitude of flux and the presence of brief flux events in only one of the two sediment traps may reflect genuine within-basin variability. Although both traps were deployed within the 500 m isobath and both were 50 m above the seafloor, they were approximately 13 km apart horizontally. Kolpack and Drake (1985) observed a seasonal redistribution of sediments within the basin resulting from winter events transporting sediments to deeper waters. This is supported by the observation of turbid plumes below sill depths in the SBB (Gorsline et al., 1984). The presence of particulate lithogenic plumes within the SBB is supported by the maxima in beam attenuation observed at depths below 75 m during the winter, summer and fall which were not associated with fluorescence maxima (Fig. 5). Sediments also accumulate at shallow depths before being redistributed within the basin during large flux events (Drake, Kolpack, & Fischer, 1972). The redistribution of material within the basin may account for the maxima of mass flux and lithogenic material observed by Thunell (1998) in his deeper trap in the late fall–early winter. It might be expected that the two traps would have shown differences in sedimentation rates during the high flux conditions of the 1997–98 El Niño as well.

Hebbeln, Marchant and Wefer (2000) reported a somewhat different pattern of seasonality in sinking flux in the Peru–Chile current. They found that the highest export rates offshore of Chile are confined to the month of September. However the peaks in fluxes of biogenic and lithogenic material were synchronous, as in the SBB. They suggested that biogenic particles remain in the deep chlorophyll maximum for up to two months before they sink out. In a six-month study in the San Pedro Basin off southern California Thunell (1998) revealed that pulses of particulate organic carbon, bSi and lithogenic material occurred synchronously in the late winter. Although these pulses coincided with high stream discharge in the winter, it remains possible that the flux of lithogenic material may be dependent on the presence of high sinking fluxes of organic material, as in the SBB. It is possible that a similar mechanism is responsible for particle export in all three of these coastal regions, export being triggered by some event, which takes place when both biogenic and lithogenic particles are present in high concentrations in the water column.

One difference between our observations and those of both Thunell, Pilskaln, Tappa and Sautter (1994) and Hebbeln et al. (2000) is that there is a decrease in the C/N ratios of the sinking particulate material in both the San Pedro Basin and the Peru–Chile current between January and July. These decreases are interpreted as resulting from changes in the proportions of terrigenous and marine organic material. The lack of a similar seasonal change in C/N ratios of sinking particulate material in the SBB may be because there the terrigenous inputs remain relatively small during normal years compared to those in the other coastal regions.

4.3. Relationship between surface and sinking particle pools

Turnover times for POC, PON, total particulate carbon (POC+calcium carbonate=TPC), bSi and lSi were calculated for summer/fall and winter/spring periods of each year by dividing the mean concentration integrated to 75 m by the mean sinking flux of each particle constituent (Table 3). POC turnover times were estimated by assuming that 10% of the TPC is carbonate. Although sinking fluxes were measured continuously, turnover times may be misleading if events were missed during the twice-monthly sampling of the upper 75 m. Prior to the 1997–98 El Niño, turnover times of all four particulate pools tended to be faster in summer/fall than in winter/spring. Thus, a larger proportion of the particles in the upper 75 m is exported during the summer/fall.

Turnover times for pools of POC, TPC, PON and bSi followed the order: PON $>$ POC $>$ TPC $>$ bSi (Table 3). Within carbon pools, POC is turned over more slowly than the TPC pool suggesting the export of carbonate is faster. In addition, a greater proportion of the bSi pool suspended in the upper 75 m is exported to 470 m depth compared to POC, TPC and PON. Slow remineralization rates of bSi relative to POC and PON and the greatest remineralization of PON is consistent with the differences in mean elemental ratios between suspended and sinking material (Table 2) and is likely a function of deeper remineralization of bSi relative to organic material (Dugdale, 1972). DeMaster, Nelson, Haden and Nittrouer (1991) also documented the enhanced preservation of bSi relative to POC during sinking in the Ross Sea. However, the C/N ratios in the Ross sea sediments indicated that was very little difference in remineralization rates between organic C and N in that water column, which contrasts to the 40% enrichment in C relative to N in the SBB during normal conditions prior to the 1997–98 El Niño.

It is widely believed that net phytoplankton ($>$20 µm) constitutes the largest fraction of sinking material (Michaels & Silver, 1988), which is consistent with high rates of sedimentation associated with spring

Table 3
Turnover times of pools of biogenic silica (bSi), lithogenic silica (lSi), particulate organic nitrogen (PON), particulate organic carbon (POC) and total particulate carbon (TPC) during summer/fall and winter/spring periods and the 1997–98 El Niño. Turnover times are based on the mean concentration integrated over the upper 75 m and the mean flux into a sediment trap at 470 m in the Santa Barbara Basin. POC turnover times were estimated by assuming that integrated POC concentrations suspended in the upper 75 m were 90% of integrated TPC concentrations

Period	Dates Profile	Dates Flux	Turnover time (days) bSi	lSi	PON	POC	TPC
Summer/fall 1995	27 Jun 95–18 Oct 95	28 Jun 95–1 Nov 95	8.3	4.5	93	65	27
Winter/spring 1995–1996	1 Nov 95–19 Mar 95	1 Nov 95–1 Apr 96	18	13	140	98	44
Summer/fall 1996	4 Apr 96–8 Oct 96	1 Apr 96—8 Nov 96	7.4	1.3	98	65	26
Winter/spring 1996–1997	6 Nov 96–26 Mar 97	8 Nov 96–14 Mar 97	12	1.6	130	74	27
El Niño 1997–1998	9 Apr 97–22 Jan 98	13 Jun–8 Aug 97; 31 Jan–11 Apr 98	12	1.4	79	53	19
Summer/fall 1998	10 Apr 98–5 Oct 98	11 Apr 98–3 Nov 98	11	2.0	–	–	–
Winter/spring 1998–1999	17 Nov 98–17 Mar 99	3 Nov 98–4 Apr 99	21	1.7	–	–	–
Summer 1999	6 Apr 99–14 Jun 99	4 Apr 99–20 Jun 99	15	2.2	–	–	–

blooms (e.g. Smetacek, Broekel, Zeitzchel, & Zenk, 1978). An abundance of diatoms would result in large fluxes of carbon and nitrogen, especially in a shallow coastal basin such as the SBB where sinking material can quickly reach the sediments. In fact, diatom blooms have been observed to aggregate and sink quickly within the SBB (Alldredge & Gotschalk, 1989). A comparison of bSi/chl a in the upper 75 m and the sinking fluxes of bSi, POC and PON at time lags of 0, 2 and 4 weeks showed no clear relationships ($r^2<0.03$ for all analyses). Thus, surface conditions during twice-monthly suspended particle profiles and continuous sediment trap measurements were sufficiently decoupled for the signals from the diatom blooms, which we sampled, not to produce discrete increases in particle flux, at these scales.

4.4. El Niño effects on surface processes

The presence of warm, nutrient-poor waters during the 1997–98 El Niño resulted in exceptionally low mean concentrations of chl a and bSi (Table 4). For the purpose of interannual comparisons, we have defined the El Niño year as the period between 1 April 1997 and 31 March 1998, based on the high SST anomalies observed in the equatorial Pacific in April 1997 (McPhaden, 1999). During 1997–1998, chl a

Table 4
Mean annual particulate concentrations integrated to 75 m at station 4 (April 1 to March 30). The average concentrations from subsequent sampling dates were used, and each day is equally weighted

Year	chl a (mg m^{-2})	biogenic silica (mmol m^{-2})	lithogenic silica (mmol m^{-2})
1994–1995	120	67	47
1995–1996	140	70	85
1996–1997	68	47	35
1997–1998	29	27	46
1998–1999	75	58	37

and bSi concentrations integrated over the upper 75 m were 29 mg m^{-2} and 27 mmol m^{-2}, respectively. During non-El Niño years, chl a and bSi concentrations were 68–146 mg m^{-2} and 47–70 mmol m^{-2}, respectively.

The low phytoplankton biomass observed in the SBB during the 1997–98 El Niño is consistent with the reductions in chlorophyll concentrations and primary productivity in the California Current observed during the 1992 El Niño (Chavez, Buck, Service, Newton & Barber, 1996). However, the effects of the 1997–98 El Niño on phytoplankton biomass within surface waters along the California coast have not been completely consistent. Lynn et al. (1998) reported that the vertically integrated chlorophyll concentrations in the California Current were similar to those of the previous 13 years. However, they did indicate that the El Niño conditions had effects on higher trophic levels; the lowest macrozooplankton abundance in their 50-year time series was measured during 1997–98. Wilkerson et al. (this issue) reports that despite lower nutrient concentrations, chlorophyll concentrations in the San Francisco Bay were higher during the 1997–98 El Niño than during the following 1999 La Niña.

This paper has been the first to address the effect of El Niño conditions on suspended elemental ratios. Our data show there were little changes in suspended elemental ratios during the 1997–98 El Niño, although Si/N and Si/C ratios were slightly depressed between May and July, 1996. The mean Si/N and Si/C ratios of 0.22 and 0.30, respectively, observed during this period reflect a small contribution of diatoms to phytoplankton biomass. Thus, if the assemblage was in balanced growth based on stoichiometric relationships between Si, N and C, less than 25% of the suspended concentrations of POC and PON could be attributed to diatoms.

The mean concentration of lithogenic silica integrated over the upper 75 m increased during the El Niño year (1997–98) relative to mean concentrations in the years both before and after the El Niño, but it was not as high as the mean concentration during 1995–96 (Table 3). We suspect that seasonal changes in the suspended pool of lithogenic material in the basin may not be well represented by profiles at the mooring site (station 4) because of the within-basin variability (Table 1; Shipe & Brzezinski, 2000). The delay in the appearance of the lSi maximum at the mooring site in the spring of 1997 (Fig. 2) may have been caused by this heterogeneous cross-shelf distribution of lithogenic material. Based on cross-channel surveys, the increases in surface lSi concentrations between December 1997 and January 1998 were confined to the basin margins (stations 1,7) (Shipe & Brzezinski, 2000). The absence of a pulse of lithogenic material in the winter of the El Niño was enigmatic, considering the high discharges from the Santa Clara River that began in November 1997 (USGS, 2000). Cross-channel lSi concentrations resolve this inconsistency as well; some of the highest lSi concentrations (up to 4.4 μmol l^{-1}) were observed between November 1997 and March 1998 at the onshore stations 1 and 2. We believe that the particles were present in the basin, but had been subducted below 75 m by the time they reached the mooring site at the center of the basin. This scenario is supported by the results of satellite remote sensing and shipboard measurements by Warrick, Mertes, Neumann, Siegel and Washburn (2000) who suggested that $<1\%$ of the particles discharged into the SBB were present in the buoyant surface plume during a large event in February 1998.

4.5. El Niño effects on sinking particle fluxes

The central region of the Santa Barbara Basin contains laminated sediments that have accumulated over the past ~20kyr (Kennett & Ingram, 1995). Previous studies of sediment cores from the SBB indicate that El Niño events are associated with changes in microfossil abundances and organic biomarker concentrations (Kennedy & Brassell, 1992). During El Niño incidents, sediment records of microfossils indicate that there are shifts toward plankton assemblages associated with warm waters (Lange et al., 1987) and decreases in fluxes of diatoms were associated with the El Niño events of the 1960s–1980s (Lange, Burke & Berger, 1990). Particle fluxes during this time series study provide further evidence that climatic events such as the El Niño phase of ENSO may be recorded in the sedimentary record. The varved layers found in the

SBB are commonly considered to be deposited with a seasonality whereby dark lithogenic material accumulates in the winter and deposition of paler biogenic material occurs in the spring. The observed changes in the seasonality of sinking fluxes imply that sediments were not be accumulating according to this model during the 1997–98 El Niño, as discussed in greater detail by Shipe and Brzezinski (2000).

The increases in sinking fluxes of POC and PON, and the possibility of higher C sequestration during the 1997–98 El Niño are not intuitive. Low suspended concentrations of bSi and chl a observed during the El Niño would not seemingly result in high flux. We believe that the increased sinking flux of POC, PON and lSi during the 1997–98 El Niño (summer 1997, later winter 1998) may be explained by changes in the proportion of particulate material being exported to 470 m depth.

Turnover times of POC and PON averaged over the El Niño period (Table 3) are 53 and 79 days, respectively. The mean sinking velocity of marine snow in coastal California waters measured in situ (Alldredge & Gotschalk, 1989) and in settling chambers (Shanks & Trent, 1980) is approximately 70 m d^{-1}. Thus, the sinking flux of POC and PON at 470 m could easily have been supported by the particulate material present in the overlying waters. An increase in the export ratio of this material could easily account for the increased sinking concentrations at depth. POC and PON turnover times during the El Niño period were the fastest during the time series, implying that the largest percentage of the suspended POC and PON pools was exported at this time. However, Thunell (1998) reported a decrease in flux of organic carbon concentrations during the 1994 El Niño. The effects of El Niño conditions on the export of organic material within the SBB may either be variable or this may be yet another example of within-basin variability, as discussed above.

C/N ratios of sinking particulate material were lower and more similar to those of suspended material in the latter half of the El Niño, between January and April 1998. This shift of C/N ratios was even more exaggerated during the post-El Nino period, resulting in the same mean ratio as in suspended material. Thus, sedimentation rates may have been faster at this time, causing a decreased opportunity for the recycling of the PON. This does not, however, explain the high fluxes of organic material in the summer of 1997.

A terrestrial source of sinking organic material during the winter of the El Niño period in the SBB is supported by observations of an increase in detritus, clay minerals, pollen grains, plant debris, and benthic plankton in the sediment trap material during December 1997 to February 1998 (Lange, Weinheimer, Reid, Tappa, & Thunell, 2000). We cannot exclude the possibility that additional terrestrial sources of C and N caused the high sinking fluxes of PON and POC in the late winter. However, C/N ratios did not increase in our trap material at that time. In general, C/N ratios of terrestrial particulate organic material are higher than those of marine organic material. Unfortunately, it was impossible to use stable isotopic analysis, which could have indicated a terrigenous source of organic material, because of the use of formalin as a trap poison.

The 1997–98 El Niño seems to be associated with a change in community composition of sinking particulate material in the SBB. The decrease in the bSi flux throughout the El Niño period may have been in part because of low suspended bSi concentrations on an annual basis suggesting a decline in the biomass of diatoms. Another indication of the change in community composition of the sinking particles was the dramatic decrease observed in Si/N and Si/C ratios. Ratios of Si/N and Si/C are more similar to those of live diatoms (Table 2), however, low annual silica production rates in the spring/summer of 1997 lead us to believe that the bulk of the organic C and N sinking at this time had been derived from a marine source other than diatoms. Mean Si production rates between April and August in the upper 75 m during 1996 and 1997 were 20 and 12 mmol m^{-2} d^{-1}, respectively (Shipe & Brzezinski, 2000). A change in the sinking assemblage to one less dominated by diatoms would have resulted in the low bSi fluxes to 470 m as well as lower apparent preservation of Si relative to C and N. A decrease in the contribution of diatoms to flux in the SBB has been documented during previous El Niño periods of 1972 and 1994 (Lange, Burke & Berger, 1990; Thunell, 1998). Chavez (1996) also observed a shift from a diatom-dominated phytoplankton community in the spring of 1990 to a picoplankton-sized community during the El Niño of 1992 in the

Monterey Bay. The ecological consequences of a shift away from a diatom-dominated plankton community must depend on the trophic position of the organisms that newly dominate the replacement assemblage. A shift from a net phytoplankton community (such as diatoms) to one dominated by picoplankton might be expected to lead to a decrease in sinking fluxes (Michaels & Silver, 1988). However, a bloom of generalist grazers might cause increases in sinking fluxes. Passow, Shipe, Pak, Brzezinski and Alldredge (2000) reported a dramatic increase in larvacean abundances in the water column at the mooring site in February–March 1997. Similar events during the 1997–98 El Nino could have caused the increases in organic and inorganic sinking fluxes associated with this event.

The turnover time for lithogenic silica in surface waters during the El Niño period was 1.4 days (Table 3). Since this turnover time was calculated using concentrations integrated over the upper 75 m, it implies a sinking rate of approximately 50 m d^{-1}. Lithogenic material in the SBB is fine-grained (Fleischer, 1972) and is unlikely to sink at this rate as individual particles. Thus, the lithogenic material may either have been scavenged by other particulates (Passow et al., 2000) or been advected laterally into the region at depths below 75 m. A combination of these two mechanisms seems likely since lSi tends to be exported at the same time as organic material and elevated lSi concentrations at the basin margins can serve as a source of sinking lSi. We believe that during the 1997–98 El Niño, elevated lSi concentrations derived from the basin's margins became associated with particulate organic material and sank, causing the observed increases in POC, PON and lSi flux. Lithogenic silica turnover times of approximately two days were not unusual during the time series (Table 3), suggesting that there is a consistent lateral input of lithogenic material and/or scavenging by other sinking particles, regardless of the presence or absence of ENSO conditions. These low turnover times are consistent with observations of increases in beam attenuation at depths greater than 75 m throughout the year (Fig. 5).

4.6. Post El Niño conditions

By 10 April 1998, there was a dramatic increase in both density and salinity in the upper 75 m of the water column and the concentrations of nitrate, dissolved silicon and phosphate recovered to the levels observed during the previous spring. A maximum in chl a and bSi concentrations both at the mooring site and at the seven cross-channel stations on April 1998 and a smaller bloom on 29 May 1998 marked the return of the seasonal cycle of biogenic particulates to pre-El Niño conditions (Fig. 2). Mean annual concentrations of chl a and bSi integrated to 75 m in 1998–99 increased by a factor of ~2 relative to 1997–98 (Table 4). There were no remarkable changes in the ratios of Si/N and Si/C in surface waters at this time. However, C/N ratios in surface waters were elevated in the fall of 1998, presumably because of an increase in the detrital content of the material, which was high in POC and low in PON and chl a (surface data not shown).

During the post-El Niño period, the export flux remained less diatom-dominated than during normal conditions prior to the spring of 1997. The export flux of bSi was consistently low (Fig. 8a) and Si/N and Si/C ratios did not recover to their former high values (Fig. 9, Table 2). C/N ratios in sinking material were consistently low until the time series ended in June 1999. The sinking ratio of C/N was 7.3, which was significantly lower than ratios prior to the El Niño (two-tailed t-test; α=0.05, $p<0.01$), was identical to the mean ratio of particulates suspended in the upper 75 m. These shifts in the relationship between surface processes and export may be further expression of a regime shift along the eastern margin of the North Pacific Ocean, as postulated by Schwing and Moore (2000). Their 54-year upwelling index showed the strongest upwelling conditions in 1999 and they report observations of ecological shifts at all trophic levels. This is consistent with the influence of strong upwelling in the SBB in the spring of 1999, when the highest nutrient concentrations and lowest temperatures (<11.5°C) were recorded in the upper 75 m of the water column.

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