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Interannual variability of new production in the southern region of the California Current

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Abstract

New primary production (P_{new}) (g C m^{-2} d^{-1}) interannual variability for offshore and inshore regions of the southern California Current from September 1969 to September 2002, using CalCOFI and IMECOCAL data (CalCOFI Lines 90, 107, and 120), was estimated. Total primary production (P_T) and the f-ratio were estimated using empirical algorithms based on nitrate and temperature ship data. Monthly new production ($P_{new} = P_T \cdot f$-ratio) values were calculated from these empirical data. Time series of P_{new} anomalies (AP_{new}, g C m^{-2} d^{-1}) were generated for each line. The period from 1977 to 1998 was characterized by frequent negative AP_{new} values ($\sim$0.10 g C m^{-2} d^{-1}), while the years 1999–2002 had relatively high AP_{new} positive values (up to 0.14 g C m^{-2} d^{-1}). The sequence of negative and positive AP_{new} values followed not only that of El Niño–La Niña events, but also the interdecadal regime shifts. A cold regime was present in our study area during the 1970s, up to 1976, after which there was a change to positive anomalies up to 1998. During the no-ENSO years, AP_{new} was approximately 20% higher than those of ENSO years.

1. Introduction

New production (P_{new}) is the fraction of total primary production (P_T) that is supported by external or "new" input of nutrients (Dugdale and Goering, 1967). Eppley and Peterson (1979) assumed that P_{new} is quantitatively equivalent to the organic matter that can be exported from the total production in the euphotic zone without the production system running down. These latter authors defined the ratio of P_{new} to P_T as an f-ratio ($f = P_{new}/P_T$) and showed that f was an asymptotic function of the magnitude of total primary production.

The fixation processes of inorganic carbon in organic matter during photosynthesis, its transformation by trophodynamics, physical mixing, transport and gravitational settling are referred to collectively as the "biological pump" (Ducklow et al., 2001). The ratio of sinking flux to primary production (e-ratio) and the f-ratio vary as functions of the pathways by which nitrogen flows among different organisms (phytoplankton, large and small grazers and bacteria), but the only way to change the absolute amount of export is to

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change P_{new}, which is usually controlled by physical factors (Frost, 1984). Thus, the description of the temporal and spatial variability of P_{new} may give us an idea of the variability of the flux of organic matter out of the surface layer.

Measuring P_T and P_{new} with bottle incubation experiments using compounds labelled with ^{14}C and ^{15}N, respectively, has been the basic methodology to generate direct estimates. However, it is very time consuming and yields very limited data with low temporal and spatial coverage. The alternative is to make indirect estimates of P_{new}. For example, Dugdale et al. (1989) and Sathyendranath et al. (1991) used remotely sensed temperature and colour to estimate P_{new}. An alternative for generating P_{new} time series for periods without satellite colour data is to use empirical statistical models that relate P_T and the f-ratio with easily measured variables such as temperature and nitrate concentration (NO_3). Coastal upwelling areas, such as that of the California Current System (CCS), are of special interest for the study of P_{new} variability because they are very productive and have a high sinking flux (Martin et al., 1987).

The aim of the present article is to quantify the interannual variability of P_{new} for the southern portion of the CCS. To accomplish this, time series of indirect estimates for three decades (1970–2002) for coastal and oceanic areas between the Southern California Bight (SCB) and Punta Eugenia (Fig. 1) were generated, using empirical relationships for P_T and f-ratio as functions of temperature and NO_3. The California Current System has clear impacts of interannual events such as El Niño–La Niña cycles (Schwing et al., 2000; Bograd and Lynn, 2001). The California Cooperative Fisheries Investigations (CalCOFI) program has generated the longest time series of oceanographic data, covering a relatively large geographic area, and very suitable for this kind of studies.

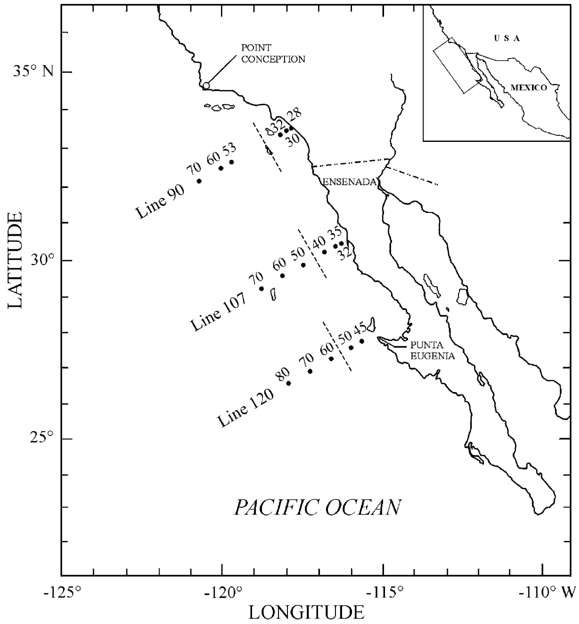

Fig. 1. Study area with CalCOFI–IMECOCAL station locations. Dashed lines separate inshore from offshore regions.

2. Data and methods

We grouped hydrographic stations into inshore and offshore areas (Fig. 1) following Lynn and Simpson (1987) criteria. For Line 90, stations 28, 30, and 32 were considered together as inshore, and stations 53, 60, and 70 as offshore. For Line 107, stations 32, 35, and 40, and stations 50, 60, and 70 were taken as inshore and offshore, respectively. And for Line 120 off Punta Eugenia, stations 45 and 50, and stations 60, 70, and 80 were taken as inshore and offshore, respectively (Fig. 1). Temperature and NO_3 data for the euphotic zone were obtained from the CalCOFI (http://www.calcofi.org) and IMECOCAL (http://imecocal.cicese.mx) programs. Investigaciones Mexicanas de la Corriente de California (IMECOCAL) started to operate in 1997 with quarterly cruises covering the CalCOFI station grid off Baja California. In situ sea-surface temperature (SST) data gaps were filled with $1° \times 1°$ longitude $\times$ latitude grid monthly averages of Comprehensive Ocean–Atmosphere Data Set (COADS) to have complete 30-year time series (http://www.pfeg.noaa.gov/products). In order to estimate the temperature vertical profiles under the sea surface, we calculated average monthly vertical profiles for each region with available hydrographic data, and their shapes were associated to the SST monthly mean. SST anomalies were calculated with the

1950–1999 time series and the long-term CalCOFI mean.

Total primary production (g $C m^{-2} d^{-1}$) integrated for the whole euphotic zone (1% E_0) and day was estimated for the period September 1969–September 2002 with the empirical relationship proposed by Smith and Eppley (1982) for the SCB: $P_T = \exp(-3.78 - 0.372TA + 0.227D)$, where TA is the monthly SST anomaly (°C) and D is the average day length (hours) for that particular month. As a first approximation, we extrapolated the application of this relationship to the southern portion of the CCS, down to Punta Eugenia.

Nitrate versus temperature linear regression equations were obtained for each region (inshore and offshore) and for each line (90, 107, 120) (Fig. 2). Linear regression was applied only to data pairs (NO_3, T°C) with NO_3 concentrations different from zero. These empirical algorithms were used to estimate NO_3 as a function of T°C to fill in the periods when no NO_3 data were available. The f-ratio for each month and for each depth was estimated as a function of NO_3 with the Harrison et al. (1987) expression, calculated from empirical data obtained in the SCB: $f = f_{max}[1 - \exp(-mNO_3/f_{max})]$, where f_{max} 90% confidence interval is 0.64 ± 0.03, and 90% interval for m is 12.10 ± 1.60. Since we estimated integrated total production, to estimate new production a proper f-ratio average for the whole water column is needed. With this objective, available CalCOFI primary productivity (PP_z) data were used. Dividing each PP_z value by the largest of the euphotic zone, normalized PP_z profiles (PP_{zR}) were calculated. With these profiles, we estimated an average shape of the primary

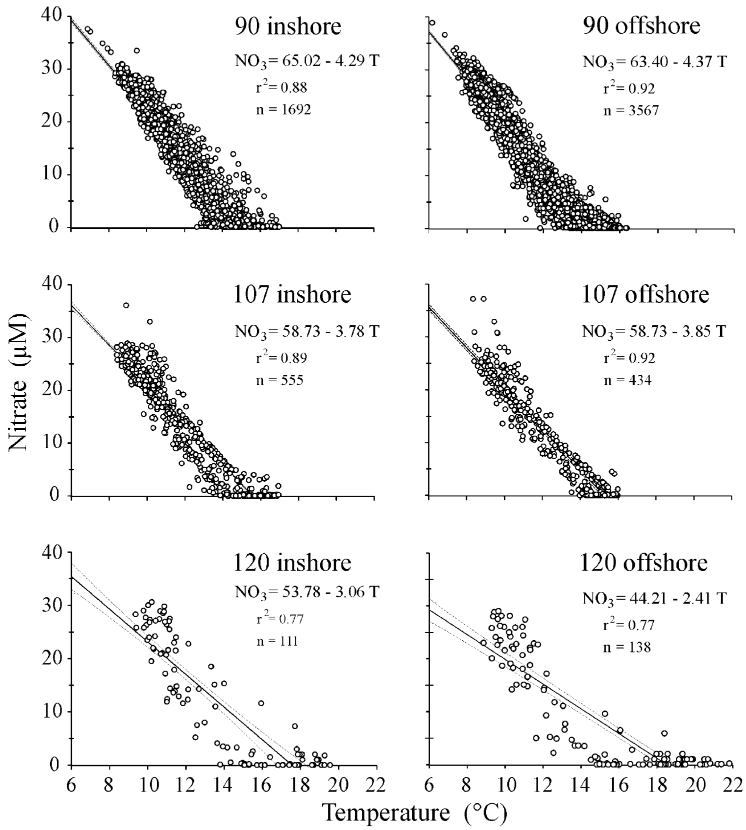

Fig. 2. Nitrate–temperature relationships and linear regression equations for each of the regions as defined in Fig. 1. Doted lines represent 95% confidence interval of the slope.

productivity profile. Then, an average f-ratio for each month was calculated using the PP_{zR} as the weighting factor. After calculating P_{new} (fP_T) as a "proxy" for euphotic zone new primary production, time series of P_{new} anomalies (AP_{new} g $C\,m^{-2}\,d^{-1}$) were generated for each region by subtracting the monthly mean of each P_{new} time series from each value. This way, an analysis of P_{new} variability can be made without a discussion on the validity of the P_{new} absolute values. Seasonal variability was taken out of the time series by calculating 12-month running means. Finally, in order to analyse the impact of ENSO events on P_{new} interannual variability the Multivariate ENSO Index (MEI) was used following Wolter and Timlin (1993, 1998) (http://www.cdc.noaa.gov/ENSO/enso.mei_index.html).

3. Results

Nitrate versus temperature linear correlation coefficients were relatively high (Fig. 2). Regression parameters were statistically different at the 95% confidence level. Data were scarcer for Lines 107 and 120 because the CalCOFI program stopped covering them in 1984 and 1981, respectively. As expected, T°C corresponding to NO_3 values close to zero decreased from south to north (Fig. 2).

The surface T°C mean for each region decreased northward, as expected. The interannual variability of the surface T°C anomalies of all six studied areas was clearly characterized by negative values in the early and mid-1970s with exception of the 1972–1973 ENSO event. Anomalies changed into positive values in 1976–1977. The period

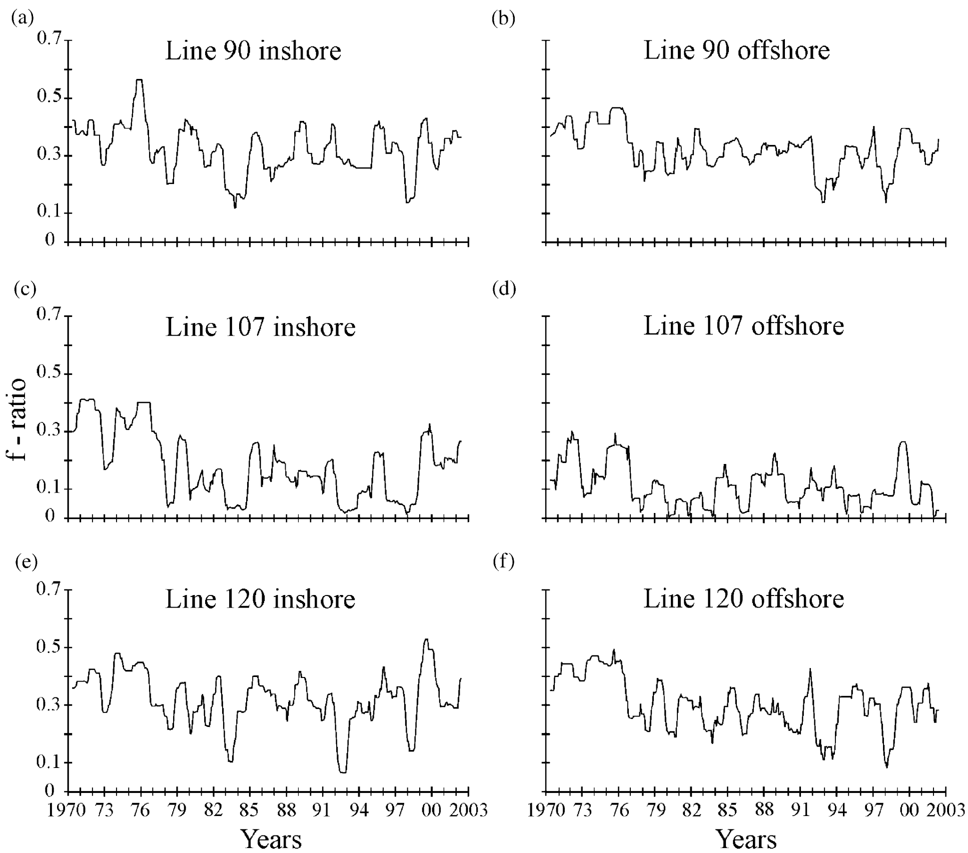

Fig. 3. Interannual variability of f-ratio (September 1969–September 2002) for the regions defined in Fig. 1. Ticks on the time scale mark the beginning of each year.

1977–1998 had mostly strong positive anomalies with greater impact inshore. Negative anomalies related to La Niña events were evident in 1988–1989, 1991, and 1999–2000 (not illustrated).

The f-ratio had large interannual fluctuations with high values in the range 0.25–0.56, and very low values close to zero. Lines 90 and 120 had similar f-ratio values with minimum values >0.07; but Line 107 had the lowest values, from close to zero to ~ 0.4 (Fig. 3). In general, low f-values corresponded to ENSO events, and high f-values to La Niña events. The maximum AP_{new} was the one for 1976 for Line 90 inshore (0.27 g C m^{-2} d^{-1}), but for Lines 107 and 120 inshore, AP_{new} values for 1976 were similar to those of 1971–1972 and 1974–1975 ($\sim$0.15 g C m^{-2} d^{-1}). The years 1999 and 2002 also had relatively high AP_{new} values (up to 0.17 g C m^{-2} d^{-1}). AP_{new} values for 1972–1973 were zero with the exception of the one for Line 90 inshore, which was negative. The period 1977–1998 was characterized by frequent negative AP_{new} values (Fig. 4). Largest AP_{new} negative values were $\sim$0.10 g C m^{-2} d^{-1}. In general, there was no clear systematic AP_{new} difference between inshore and offshore areas. In agreement with lowest f-ratio values, Line 107 had the lowest P_{new} average values (Fig. 4, Table 1).

In order to estimate more clearly the effect of ENSO events on P_{new}, we calculated the fall–winter P_{new} average for the year before (-1), during (0), and the 2 years after ($+1$, $+2$) each of the six events reported in the literature for the period under study, and we plotted these mean for each area. The MEI also was drawn to indicate the ENSO event duration (Fig. 5). In general, ENSO years had lower P_{new} values than the years before and after the events, with values falling down to as low as $<20\%$ during ENSO years, with respect to previous years. The most obvious exception was Line 120 offshore for the weak 1987–1988 ENSO event (Fig. 5). During ENSO years P_{new} values were sometimes close to zero, but in other similar events they were as large as $\sim$0.15 g C m^{-2} d^{-1}, as during the 1972–1973 ENSO event. In some few cases, P_{new} values were relatively low the year before, during and after the ENSO. However,

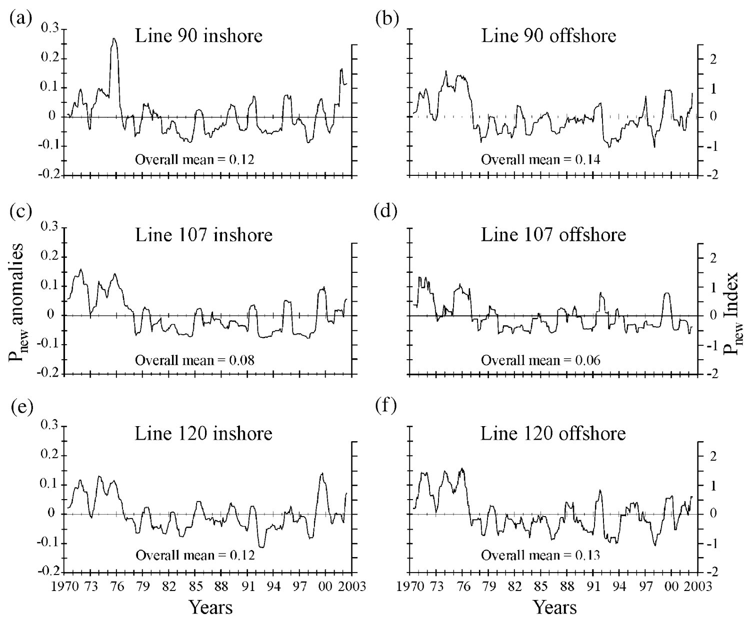

Fig. 4. New production anomalies (AP_{new}, g C m^{-2} d^{-1}) interannual variability (September 1969–September 2002) for different regions within the CCS as defined in Fig. 1. Ticks on the time scale mark the beginning of each year. The mean of the whole new primary production data set for each region is shown.

Table 1
Mean annual new primary production (g C m^{-2}) for each line, overall average for the three lines together, standard deviation and coefficient of variation of all monthly estimates

	Line 90	Line 107	Line 120	Average	S.D.	% C.V.
1970	0.144	0.128	0.168	0.147	0.020	14
1971	0.223	0.204	0.251	0.226	0.018	8
1972	0.124	0.136	0.178	0.146	0.026	18
1973	0.224	0.092	0.227	0.181	0.059	33
1974	0.228	0.117	0.214	0.186	0.046	25
1975	0.350	0.197	0.250	0.265	0.056	21
1976	0.166	0.135	0.151	0.151	0.028	18
1977	0.123	0.074	0.113	0.103	0.020	19
1978	0.087	0.039	0.084	0.070	0.021	30
1979	0.142	0.090	0.143	0.125	0.025	20
1980	0.124	0.042	0.074	0.080	0.029	37
1981	0.072	0.016	0.087	0.058	0.028	48
1982	0.137	0.035	0.122	0.098	0.042	43
1983	0.059	0.009	0.052	0.040	0.021	51
1984	0.092	0.045	0.112	0.083	0.034	41
1985	0.153	0.064	0.128	0.115	0.038	33
1986	0.070	0.030	0.086	0.062	0.022	36
1987	0.094	0.076	0.101	0.090	0.011	12
1988	0.131	0.062	0.150	0.115	0.035	30
1989	0.135	0.048	0.107	0.097	0.034	35
1990	0.106	0.032	0.078	0.072	0.026	37
1991	0.195	0.096	0.176	0.156	0.042	27
1992	0.059	0.040	0.027	0.042	0.023	55
1993	0.063	0.048	0.060	0.057	0.022	39
1994	0.099	0.021	0.101	0.074	0.035	48
1995	0.158	0.078	0.150	0.129	0.038	30
1996	0.133	0.018	0.119	0.090	0.048	53
1997	0.086	0.021	0.089	0.065	0.030	45
1998	0.099	0.027	0.081	0.069	0.028	41
1999	0.193	0.152	0.215	0.187	0.033	18
2000	0.110	0.039	0.101	0.083	0.030	36
2001	0.219	0.069	0.137	0.142	0.056	39
2002[a]	0.234	0.096	0.212	0.181	0.066	36

[a] Only for January–September.

there was no particular geographic trend for these behaviours (Fig. 5).

4. Discussion

Large temporal and spatial scale physical forcing affecting the southern portion of the CCS during the period 1970–2002 resulted in interannual variability of temperature and NO_3 input to the euphotic zone, which in turn affected new primary production (P_{new}). A cold regime was present in our study area during the 1970s, up to 1976, after which there was a change to positive temperature anomalies (Stephens et al., 2001). The warm regime started in 1977 and continued at least until 1998 in the CCS (Moser et al., 2001). According to Minobe (1999), the 1999–2000 La Niña event marks a shift back to the cold regime, with oceanographic conditions similar to those of 1948–1976.

Interannual variability of new primary production shows high values during the first half of the 1970s, decreasing abruptly with the 1976–1977 ENSO event (Fig. 4), with relatively small fluctuations around the mean during 1977–1998, and with some indication of increasing again to high values starting in 1999. Minimum new primary production values were associated mostly to ENSO events. This is the result of the very well-known effect of higher water column stratification and deepening of the thermocline. However, the effect of ENSO events on primary production clearly depends on the stage of the North Pacific interdecadal oscillation. The strong ENSO event of 1972–1973 did not cause large negative new production anomalies because it happened during a cold regime, while the ENSO events of 1982–1983, 1992–1993 and 1997–1998 caused large negative production anomalies during the warm regime. Reyes-Coca (CICESE, pers. comm.) indicated that while precipitation on Baja California generally increases during ENSO events, the 1972–1973 event did not cause a precipitation significantly larger than the long-term mean, which also shows the effect of the interdecadal variation in other geophysical variables of our study area.

A qualitative characterization of the composition of sinking particulate organic carbon, as well as quantitative information on nutrient recycling within the euphotic zone, can be provided by the f-ratio. According to Eppley and Peterson (1979), nutrient recycling within the euphotic zone varies regionally with the total production rate. The number of times a nutrient element is recycled in the euphotic zone before sinking out in particulate form is given by $r = (1 - f)/f$. Considering our long-term mean f-ratio value ($\sim$0.3) from Lines 90 and 120, the recycled ratio is $\sim$2.3. This means

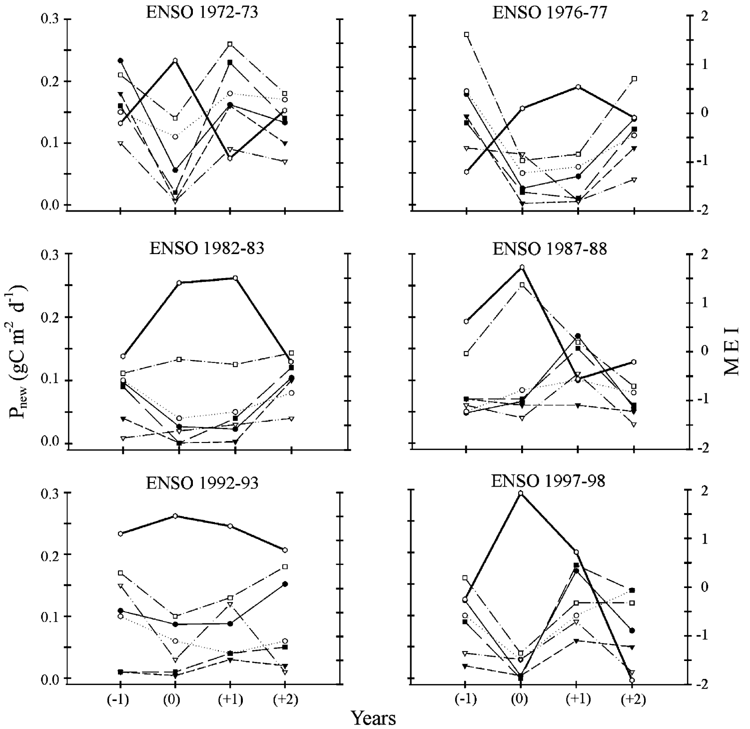

Fig. 5. Fall–winter average new production (P_{new}, g C m^{-2} d^{-1}), and MEI for the year before ENSO (-1), during the event (0), and 1 and 2 years after ($+1$, $+2$) for the six events in the period 1970–2002. Clear circles represent Line 90 offshore, black circles 90 inshore, clear triangles 107 offshore, black triangles 107 inshore, clear squares 120 offshore, black squares 120 inshore. Thick line represents MEI.

that, as an average, the number of times nutrients (for example, NO_3) recycle in our study area is greater than two, and after that, they sink out of the euphotic zone.

Karl et al. (2001) showed an 11-year time series of the ratio of sinking flux to primary production (*e*-ratio) for the Bermuda and Hawaii JGOFS sites. These latter authors reported a great time variability of the *e*-ratio with values in the range 0.02–0.21 for Bermuda, and 0.02–0.15 for Hawaii. Our *f*-ratio values also had great time variability with ranges of 0.15–0.56, 0.01–0.42, and 0.05–0.55 for Lines 90, 107, and 120, respectively. *Strictu sensu*, it is not correct to compare the Karl et al. (2001) *e*-ratio values with our *f*-ratios. Nevertheless, it is interesting to see that variability of both is similar, and as expected *e*-ratio values are smaller than *f*-ratios. Their *e*-ratios are smaller mainly because of the organic matter degradation in their way down to the bottom, only the most refractive particles reach the bottom, and because the Bermuda and Hawaii sites are less productive than our region within the CCS, which possibly produces smaller *f*-ratio averages for the euphotic zone.

Based on data from a sediment trapping program, Thunell (1998) reported that for the Santa Barbara basin, a coastal upwelling zone off southern California, export ratios are inversely related to total primary production, and this may be due to increased advective transport during the highly productive upwelling season. Thus, P_{new} seasonal variability in our study area may not be in phase with the *e*-ratio seasonal variability. However, based on his particle flux data, Thunell (1998) indicated that production in the Santa Barbara basin is reduced during ENSO events. This indicates that in the interannual scale both, P_{new} and biogenic sediment flux may vary in phase.

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