TEMPORAL PATTERNS OF SILICEOUS FLUX IN THE SANTA BARBARA BASIN: THE INFLUENCE OF NORTH PACIFIC AND LOCAL OCEANOGRAPHIC PROCESSES

ELIZABETH L. VENRICK
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0227
USA
evenrick@ucsd.edu

FREDA M. H. REID
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0227
USA

AMY WEINHEIMER
Integrative Oceanography Division
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California 92093-0227
USA

CARINA B. LANGE
Universidad de Concepción
Departamento de Oceanografia and Centro FONDAP-COPAS
Casilla 160-C, Barrio Universitario, Concepción
Chile

E. P. DEVER
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, Oregon 97331-5503
USA

ABSTRACT

This paper examines the relationships between fluxes of biogenic siliceous microparticles and two indices of climatology and regional oceanography in the Santa Barbara Channel. As an index of large-scale processes, we use the Pacific Decadal Oscillation Index (PDO). As an index of small-scale processes, we use the first Empirical Orthoganal Function (EOF) of objectively mapped local circulation patterns. Local circulation is correlated with basin-wide climate.

Results are consistent with the hypothesis that one influence of climate on phytoplankton flux is initially exerted through climate-driven effects on local circulation. The response of siliceous phytoplankton to changes in circulation and climate occurs relatively rapidly, over periods of a few weeks, consistent with flux being directly mediated by advection of waters from different sources. The maximum response of radiolarians to basin-wide conditions is delayed for several months, and appears to be more indirect than that of phytoplankton, perhaps buffered against environmental changes by differences in trophic level or depth range.

Several flux events did not have apparent relationships with either oceanic climate or local oceanography. These anomalies lasted for one to four months and may represent the limits of resolution of flux data.

INTRODUCTION

Much of what we know about the Earth before written history has come from the sedimentary record. Typically, sedimentary resolution is coarse, and information derived from it is broad-scale. As concern about anthropogenic effects grows, our paleoecological questions shift to modern times and to smaller scales. To accurately extract information from more recent sediments and to interpret the smaller scales of modern changes, it is important to understand the mechanisms that transfer materials through the water column and into the sediments and factors affecting their preservation (e.g., Sancetta 1989, 1992; Lange et al. 1994; Romero et al. 2000, Venrick et al. 2003). These define the ultimate resolution of what we can learn.

The Santa Barbara Basin is an active area for such research. A unique combination of hydrography and bathymetry results in the deposition and preservation of seasonal lamina (Schimmelmann and Lange 1996). Cores from the Santa Barbara Basin have been used to reconstruct events of the distant past (e.g., Kennett and Ingram 1995; Behl and Kennett 1996; Berger et al. 1997; Biondi et al. 1997; Berger and Lange 1998; Field and Baumgartner 2000) as well as more recent events (Soutar and Isaacs 1974; Lange et al. 1987, 1990; Schimmelmann and Tegner 1991; Schimmelmann et al. 2003; Field 2004).

This paper examines results from one of two recent sediment trap studies in the Santa Barbara Channel (SBC) that examines the relationship between the downward flux of material and conditions in the overlying water column (e.g., Thunell et al. 1995; Thunell 1998; Lange et al. 1997, 2000; this study; also Shipe and Brezinski 2001; Shipe et al. 2002). Our sediment trap data are accompanied by an extensive and synoptic set of observations on near-surface circulation (Dever et al. 1998; Harms and Winant 1998; Winant et al. 1999, 2003; Dever 2004) which reflect environmental processes over short time scales. This near-surface circulation is expected to advect waters of different histories and biomasses into the SBC. The goal of this paper is to examine the relationships between fluxes of biogenic siliceous microparticles and the oceanography of the overlying euphotic zone from two-week to interannual scales. We first remove the annual cycle from all data sets. We then attempt to separate the effects of the large-scale, low-frequency variability—represented by climate-driven, basin-wide sea surface temperature fluctuations—from the smaller-scale, higher-frequency events represented by changes in local circulation patterns. The degree to which we succeed helps us understand the effective resolution of laminated sediments, such as those found in the Santa Barbara Basin.

This paper is the second in a series of three. The first paper (Venrick et al. 2003; discussed below) compares the composition and flux rate of siliceous phytoplankton in the sediment traps to phytoplankton samples collected in the overlying euphotic zone. The final paper will examine the species composition of the flux of siliceous phytoplankton and radiolarians in the context of the overlying oceanography. Because much of our current information about bio-geo-chemical flux is derived from chemical measurements of bulk flux, we first examine our data in a comparable fashion—as total flux of siliceous particles.

BACKGROUND INFORMATION

Geographical Setting

The Santa Barbara Channel (SBC) is approximately 100 km long and 50 km wide at its widest point (fig. 1). It is bordered by Southern California on the north and east and by the Channel Islands on the south and west. The Santa Barbara Basin is a bottom depression in the western center of the channel, and reaches depths in excess of 550 m. Shallow sills at the eastern and western edges inhibit bottom water renewal (Bograd et al. 2002). Thus, the basin is generally anoxic or dysoxic, the depositional history is preserved on a fine scale, and seasonal resolution is possible (Emery and Hülsemann 1962; Thunell et al. 1995).

Climate

Over the seven years of this study, the best sampled scale of climatic variability in this region is the El Niño-Southern Oscillation (ENSO) cycle. This is a quasi-periodic alternation of warm and cold near-surface waters in response to large-scale changes in atmospheric pressure gradients and oceanographic events in the equatorial region (Glantz 2003). During the present study there was a moderate warm-water event (El Niño) in 1993 (a resurgence of the 1991–92 equatorial event), a strong El Niño event in 1997–98, and a strong cold-water event (La Niña) in 1999 (fig. 2A). Although weak to moderate La Niña conditions developed at the equator in late 1995, the response of the North Pacific was unusual, and local expression of La Niña was weak and inconsistent (Schwing et al. 1997). In contrast, the Pacific Decadal Oscillation Index (PDO), based on North Pacific temperatures, indicates a cold-water period in the latter half of 1994, which was not apparent at the equator and not a true La Niña.

ENSO signals may be transmitted into the SBC both oceanically, by coastally trapped waves moving north from the equator, and atmospherically, by changes in midlatitude circulation and consequent changes in the strength of longitudinal winds along the coast (Huyer and Smith 1985; Lynn and Bograd 2002; Strub and James 2002a, b). These signals have different propagation times and different latitudinal expressions and may ultimately reinforce or counteract each other. The ultimate expression of an ENSO event may depend upon ambient conditions (Palacios et al. 2004). There are differences between the timing of surface and subsurface oceanographic responses and differences among the timing and magnitude of local biological responses (Huyer and Smith 1985; Hayward 2000; Lynn and Bograd 2002), and these are all confounded in the biological record that is preserved in sediments.

The sampling period of the present study began in the summer of 1993 and partially overlapped the resurgence of the 1991–92 event; it included the 1994 cold-water event. The data overlap the large ENSO cycle in 1997–99 but are punctuated by a data gap between April 1998 and April 1999. Our data were collected during the development of the 1997–98 El Niño and the peak and decline of the subsequent La Niña.

Regional Oceanography

The California Cooperative Oceanic Fisheries Investigations (CalCOFI) has conducted regular surveys of the California Current system since 1949. One station above the Santa Barbara Basin has been continuously sampled, allowing the conditions in the SBC to be interpreted in a broader spatial context (Hayward and Venrick 1998; Venrick 1998a, b).

From the CalCOFI data (e.g., reviewed by Hickey 1979; Lynn and Simpson 1987; Bray et al. 1999) it is known that there are two primary sources of water in the SBC. From the west (north), water is coastal, and includes cold, upwelled water from the region between Point Conception and Point Arguello. From the east (south), water is warm saline water from the Southern California Bight. This latter water has a complex and variable origin that includes the Central Pacific, the East Tropical Pacific, and modified water from the California Current. The core of the California Current rarely penetrates into the SBC directly (Bray et al. 1999).

In general, the California Current ecosystem during warm-water periods, such as El Niño, is characterized by anomalously warm near-surface temperatures, reduced flow (and/or a more offshore position) of the California Current, anomalously strong and broad coastal countercurrents especially during the winter months, and a deeper than usual pycnocline and nutricline (Hayward et al. 1995, 1999; McGowan et al. 2003). Macrozooplankton biomass is reduced (Chelton et al. 1982; Roemmich and McGowan 1995). During cold-water periods, reverse conditions occur (Otero and Siegel

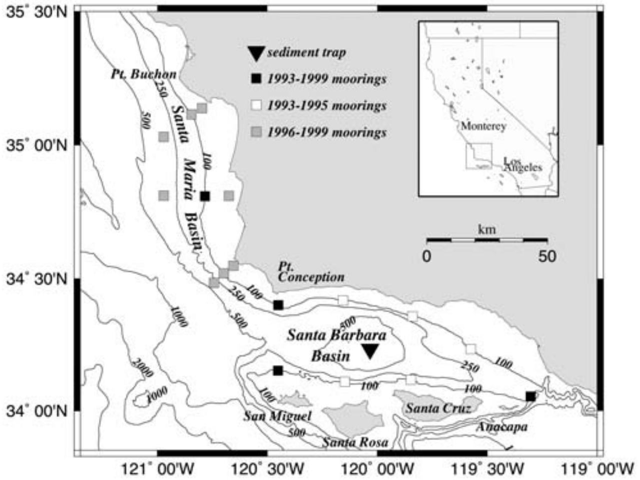

Fig.1. Geography and topography of the Santa Barbara Channel and Santa Barbara Basin, indicating location of the sediment trap and the moorings.

2004) and zooplankton biomass is elevated (Chelton et al. 1982; Hayward 2000; Bograd and Lynn 2001; McGowan et al. 2003; Peterson and Schwing 2003). Paradoxically, the regional response of chlorophyll to the ENSO cycle is less pronounced than that of zooplankton (Hayward 2000; Otero 2002). Recent sediment trap studies have indicated a reduction in flux of biogenic silica during warm-water events, consistent with the more oligotrophic characteristics observed in overlying waters (Lange et al. 1987, 2000; Shipe et al. 2002).

Local Circulation

Since 1993, a number of moorings have been located in and north of the Santa Barbara Channel (fig. 1). These, together with drifter releases, hydrographic surveys, and anemometer measurements, have provided detailed information about the near-surface current patterns in the SBC (e.g., Dever et al. 1998; Harms and Winant 1998; Winant et al. 1999, 2003; Dever 2004). At the eastern (southern) entrance, annual mean flow into the channel at the surface is poleward. However, this reverses seasonally, being generally equatorward between February and June. At the western (northern) mouth, mean flow is poleward along the northern shore and equatorward along the southern. Overall, equatorward transport is greatest during the spring and weakest during the winter.

Shorter-term local circulation is a complex pattern of near-surface currents and reversals, filaments, and eddies. These have been described as synoptic states (Harms and Winant 1998; Dever et al. 1998; Winant et al. 2003; Dever 2004) that have seasonal cycles as well as extreme short-term variability in their duration and intensity. The state most frequent in the spring is characterized by a generally equatorward flow. This "upwelling" state occurs when equatorward winds are strong, and poleward along-shelf pressure gradients are weak. The winds promote upwelling north of Point Conception and the weakened pressure gradients allow newly upwelled water to enter the channel through the western mouth. There may be sporadic incursions of upwelled water during other seasons as well. Although this advection of newly upwelled water is thought to be a major source of phytoplankton biomass and new nutrients in the SBC, there is evidence for areas of upwelling within the Channel (Oey et al. 2001; Otero 2002).

In the fall and winter, flow is generally poleward, bringing low nutrient water from the Southern California Bight through the eastern channel proceeding along the coast and exiting to the west. This "relaxation" state is associated with weakened winds combined with a strong poleward pressure gradient.

Superimposed upon these tendencies are patterns of cyclonic recirculation in the western channel, brought about by the interaction of the basin-wide pressure gradients and local wind stress and topography (Dever et al. 1998; Winant et al. 1999; Dever 2004). Of 235 drifters released at various locations within the SBC, the median residence time was seven days (Winant et al. 1999). It is clear that the SBC cannot be considered a closed system, in spite of the recurrent internal circulation patterns.

Local Phytoplankton

Chlorophyll in the euphotic zone (0–200 m) above the sediment trap has a seasonal cycle, superimposed upon considerable interannual variability (Venrick 1998a; Otero and Siegel 2004). Maximum values, up to 22 mg m^{-3}, tend to occur in the spring. Near-surface chlorophyll levels are related to the surface-flow patterns of upwelling and relaxation (Otero 2002; Otero and Siegel 2004). During upwelling, water is advected into the SBC from the north, and chlorophyll concentrations are generally between 2 and 10 mg m^{-3} throughout the SBC. Poleward flow is associated with reduced chlorophyll levels. Very low near-surface chlorophylls were seen during the El Niño in October and November 1997. Siliceous species, on the average, comprise 90% of the total number of phytoplankton cells in the near-surface waters above the Santa Barbara Basin (Venrick et al. 2003). The correlation between the abundance of these siliceous species and the concentration of near-surface chlorophyll is also high ($\rho = 0.90$; Venrick unpublished data). The flux of siliceous phytoplankton in the present study reached a maximum correlation with the total abundance of near-surface siliceous phytoplankton when the flux lagged the near-surface population by six to eight weeks (Venrick et al. 2003). Comparison of this lag time with the seven-day median residence time of a parcel of water suggests that much of the material reaching the sediment trap originates outside the SBC; the exact footprint of the trap, however, is uncertain (Venrick et al. 2003).

MATERIALS AND METHODS

Climate

As a general index of climate we use the Pacific Decadal Oscillation index (PDO), the first orthogonal axis of detrended Pacific sea-surface temperature north of 20°N (Mantua et al. 1997). Although developed primarily as an index of interdecadal oscillation, the PDO captures large-scale patterns of sea-surface temperature that are prevalent on ENSO as well as decadal time scales. Because it is based on parameters from the North Pacific, the PDO may be a more sensitive index of the broad regional conditions of our study area than more tropically weighted indices, such as the Multivariate ENSO Index or the Southern Oscillation Index.

Local Circulation

Between 1993 and 1995, current meter data were collected primarily in the Santa Barbara Channel. Between 1996 and 1999, these data were collected primarily in the Santa Maria Basin. Four long-term current meter moorings spanned both parts of the study. To produce long-term continuous time series, all available current meter data were objectively mapped on a curvilinear orthogonal grid. The flow field was represented as one of the three flow states defined in Dever (2004) plus a residual field. Both the large-scale and the residual fields were mapped using realistic spatial decorrelation scales (Dever 2004). Empirical Orthogonal Functions (EOFs) were then calculated from the objectively mapped flow fields. Values calculated every six hours were averaged into appropriate intervals for comparison with the PDO and fluxes.

Flux

The sediment trap was a 13-cup trap with a 0.5 m^2 collection area, located near the center of the Santa Barbara Basin (34°14'N, 120°02'W; fig. 1) about 50 m above the bottom (Thunell 1998). One hundred and twenty seven samples of two-week duration were collected sequentially between 19 August 1993 and 12 April 2000. There were four traps set over a one-week period (June 1997 and May 1999). In the following study, the trap date is the midpoint of the trap collection period. Because of trap malfunctions there are no samples between 10 April 1998 and 5 May 1999, nor from several shorter intervals.

Trap samples were poisoned in the field with $HgCl_2$. Splits of the original sample (usually 1/16–1/64) were washed through a 45 µm sieve, acid-cleaned (Wigley 1984), and mounted on replicate slides with Naphrax and Canada Balsam. Thus, abundances of very small cells may be underestimated (Venrick et al. 2003). Subareas of Naphrax slides were counted for siliceous phytoplankton skeletons (diatoms and silicoflagellates) using an Olympus phase contrast microscope and a magnification of 250X, or 650X for spores and small valves (see Lange et al. 1997 for details on methodology). Subareas of the Canada Balsam slides were counted at 100X for radiolarians. Diatom flux often occurs as single valves. Where appropriate, valve flux was converted to whole cell flux to allow direct comparison of phytoplankton and radiolarian fluxes. For convenience, results are presented as cells/10 cm^2/day (= cells/m^2/day x 10^{-3}).

Statistical Analyses

The short length and discontinuous nature of the flux data limits the usefulness of many quantitative analytical techniques. We emphasize nonparametric techniques, which may be more powerful than standard procedures when the underlying assumptions, such as the assumptions of normality or continuity, are violated (Conover 1999). Correlograms are based upon Spearman's rank correlation coefficient, ρ. Traditional significance levels (p = .05 and p = .001) are shown as qualitative references but because of the large number of correlations and their lack of independence, the correlation coefficients are not probabilistic. Data from the four traps set over a one-week period (June 1997 and May 1999) have been pooled or omitted from the correlation calculations.

We removed the annual cycle from all variables. This cycle was estimated with monthly means for the PDO, with a 13-day running median for the EOF #1 and with a five-point running median (which has a median span of 13 days) for the fluxes of phytoplankton and radiolarians. The median was selected instead of the mean because of the variability and skew of the flux data. To implement correlations between flux (deviations from the annual cycle; two-week measurements) and the basin-wide characteristics (PDO deviations calculated as monthly values), we used the average value of the PDO index experienced by each trap.

RESULTS

Climate

Many studies have investigated the characteristics of the PDO (fig. 2A; Mantua et al. 1997; Zhang et al. 1997). Between 1990 and 2000 there was an annual cycle with warmer water (positive PDO) occurring May–July and colder water (negative PDO) in October–January (fig. 2B). The annual cycle accounts for 23% of the total variability of the PDO, and its removal does little to alter the basic interannual patterns (fig. 2C). For this study, we define extreme warm-water periods as those with

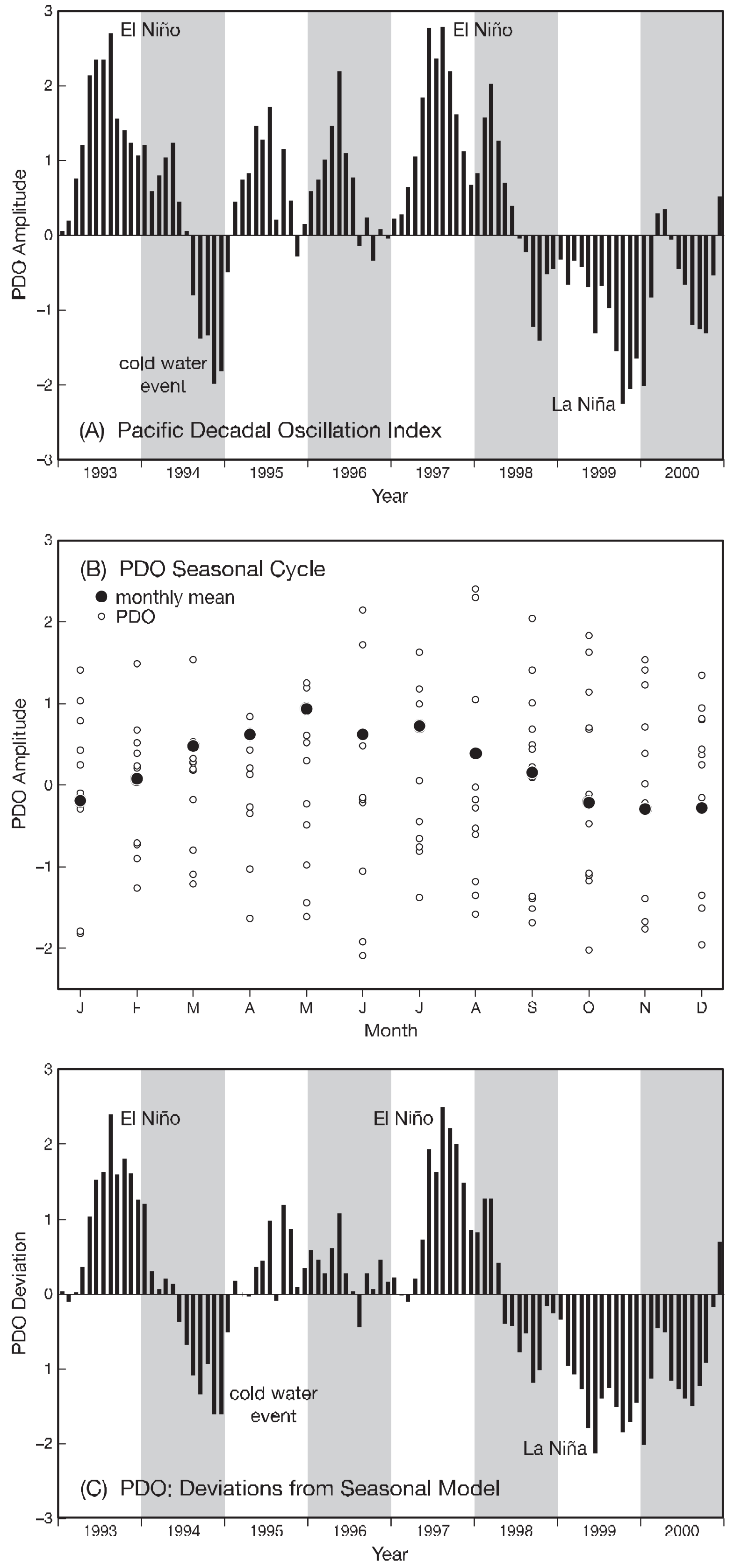

Fig. 2. The Pacific Decadal Oscillation Index, 1993–2000. A) PDO values; B) Monthly values and monthly means; C) Deviations from seasonal means.

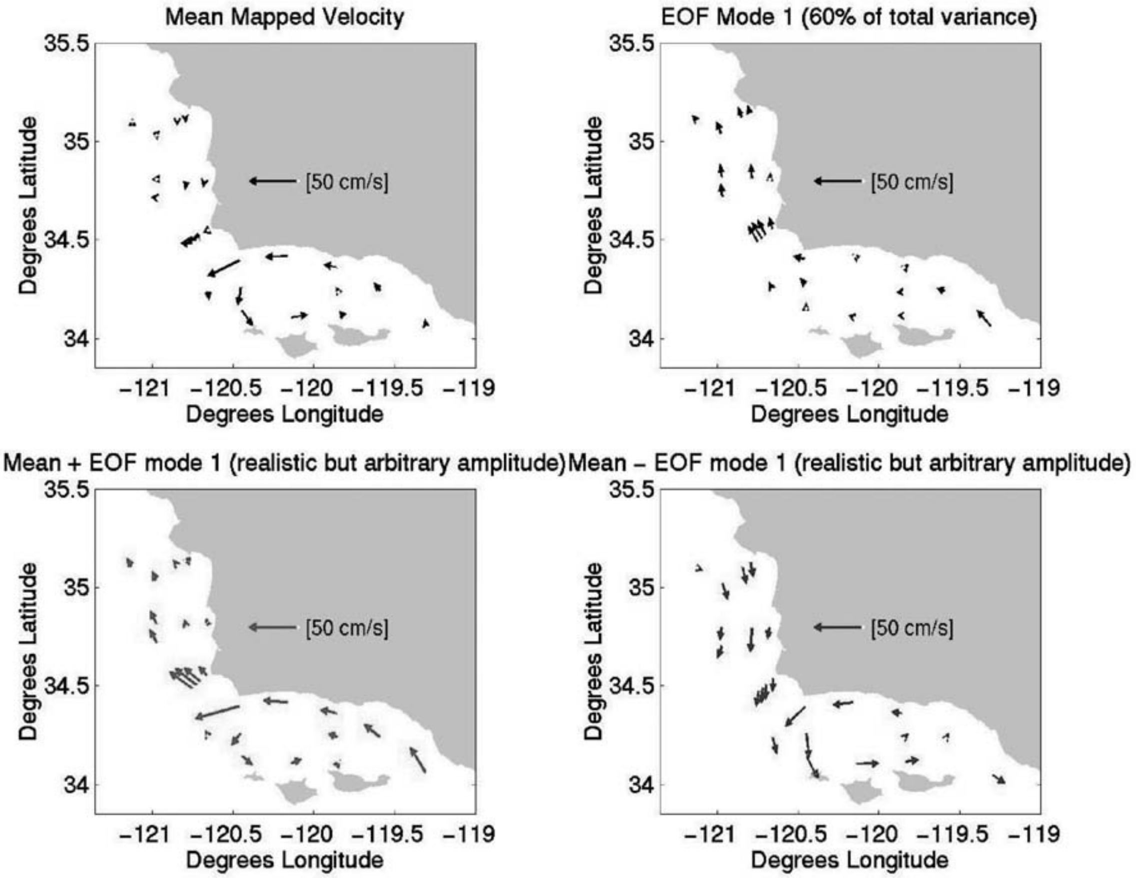

Fig. 3. Local circulation patterns. A) annual mean flow; B) spatial pattern of EOF #1; C) the relaxation state, approximated by the mean flow plus EOF #1; D) the upwelling state, approximated by the mean flow minus EOF #1. To reconstruct plots C and D, eigenvectors have been given arbitrary but realistic amplitudes.

deviations greater than 1.62. Ten percent of the PDO deviations fall into this category during two periods: June–August 1993 plus October 1993, and June–October 1997. Extreme cold-water periods are those with deviations less than −1.50 and include 10 months in two periods: September 1994 plus November–December 1994, and May–June 1999 plus September–November 1999 and January and August 2000.

Circulation

The first EOF of near-surface circulation in the Santa Barbara Channel accounts for 60% of the variability and expresses alternation of the poleward-equatorward tendencies in the flow (fig. 3). When added to the mean velocity field, the flow is poleward, strongest along the coast, with a reduced equatorward flow in the western channel (fig. 3C). This corresponds to the relaxation state defined in previous studies (Dever et al. 1998; Harms and Winant 1998; Winant et al. 2003; Dever 2004). When EOF #1 is subtracted from the mean velocity field, the upwelling state is reproduced: dominant flow is equatorward and strongest on the southern edge of the channel, with weakened poleward flow along the coast (fig. 3D). During the study period, the persistence of either state was short-lived (fig. 4A). Although any magnitude of EOF #1 occurred at any time of year, there was a seasonal cycle (fig. 4B) with upwelling (negative) most likely to occur between March and June and relaxation (positive) most likely in July–January.

The seasonal model based on a 13-day running median accounts for about 50% of the variability of EOF #1. When the seasonal cycle is removed, much of the remaining variability occurs over scales of days to weeks (fig. 4C). Interannual variability is most evident during the large El Niño of 1997 when circulation between February and December was consistently more poleward than usual. This was followed by an extended period in 1998 when La Niña conditions were developing and circulation tended to be more equatorward than usual.

Cross-correlation between PDO and EOF #1 (seasonality removed; fig. 5) shows the strongest relationship between minus four weeks (circulation leading the PDO) to four weeks (PDO leading circulation). The positive correlation indicates that equatorward flow is associated with cool North Pacific waters and vice versa. The relatively high correlation at negative lags suggests

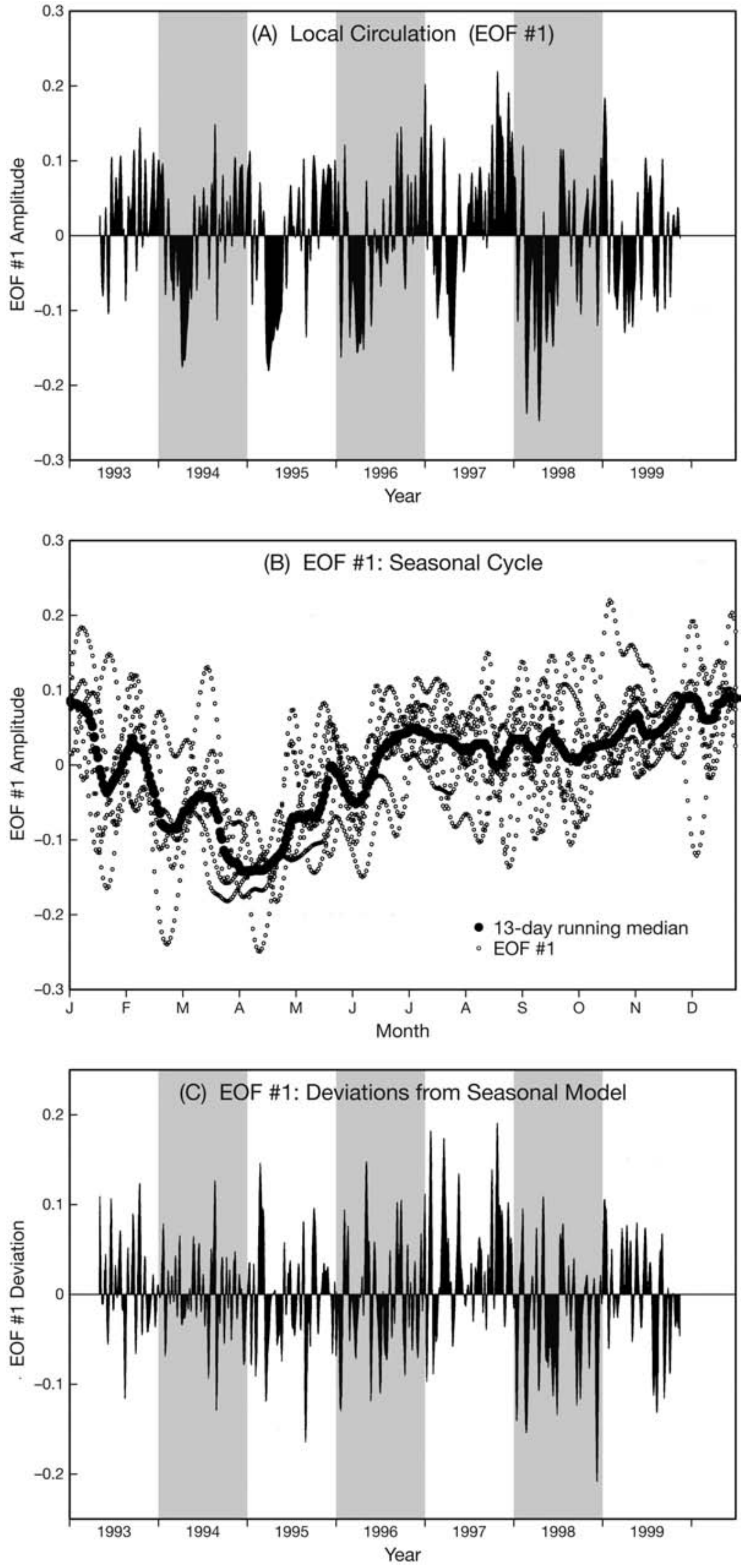

Fig. 4. Temporal sequence of local circulation patterns 1 May 1993–6 November 1999. A) Magnitude of EOF #1; B) Daily values by month and 14-day running median; C) Deviations from seasonal model.

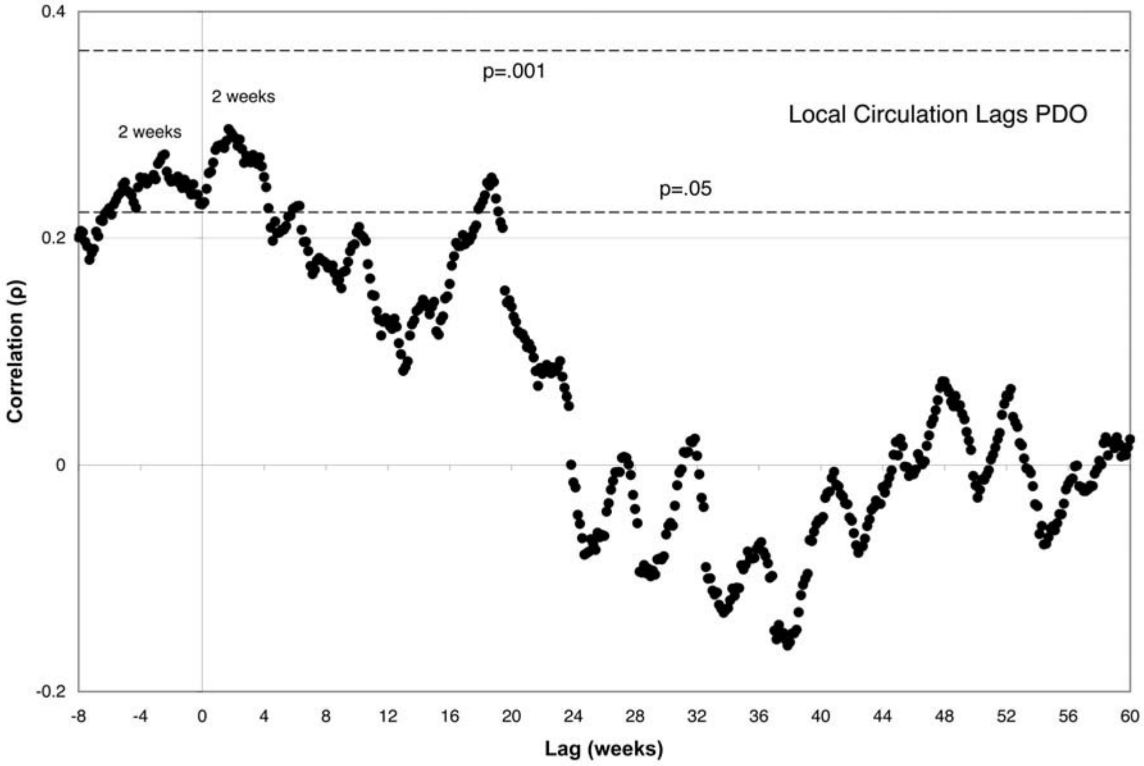

Fig. 5. Cross-correlation (Spearman's ρ) between climate (PDO) and local circulation (EOF #1) with circulation lagging climate. Input values are deviations from seasonal models. "Confidence" bands, based upon changing degrees of freedom, are given as general references only.

that an initial influence of climate change may be directly exerted on local oceanography through changes in local circulation before the full development of the basin-wide sea-surface temperature patterns. This is consistent with the model of large-scale climatic influences being propagated atmospherically, and influencing local wind patterns and near-surface circulation.

Flux

During this study, siliceous biogenic fluxes were dominated by diatoms (95.6%). Radiolarians contributed 3.0% and silicoflagellates 1.4%. Total flux of phytoplankton (diatoms and silicoflagellates) ranged over nearly four orders of magnitude, between 0.86 and 11,162 cells/10 cm^2/day (fig. 6A). Major peaks in flux occurred in spring. There was a sizeable peak in flux between mid-April and mid-May in every year except the El Niño years 1997 (when the trap malfunctioned in early May) and 1998 (when trap malfunctioned in mid-April). The spring peak was the annual maximum except in 1996 when the maximum flux occurred in November and the spring flux was a secondary peak. Phytoplankton dominated total biogenic flux, imposing its seasonal cycle on that of total biogenic flux. A five-point running median captures the major elements of the seasonal cycle of phytoplankton (fig. 6B), accounting for 37% of the variability of the original data. Seasonality is demonstrated by a χ^2 test of flux differences at two-month intervals (December–January, February–March, etc.; $p < .025$). Half of the resultant χ^2 value is contributed by the excess of high values in April and May.

Maximum radiolarian flux was two orders of magnitude less than that of phytoplankton, ranging between 0.65 and 54 cells/10 cm^2/day (fig. 7A). Radiolarian flux exceeded phytoplankton flux in only five traps, all during February and March (1995, 1998, 2000). The highest fluxes of radiolarians tended to occur in the fall (fig. 7B). However, in 1999, coincident with the development of a large La Niña, fluxes increased dramatically, with maximum rates in late spring and summer and only a minor peak the following fall. The five-point running median (fig. 7B) is relatively insensitive to the 1999 outliers and indicates the general tendency for a fall increase in flux, with lower but variable fluxes the rest of the year. Removal of the seasonal model reduces the variability by 50%. A χ^2 test of fluxes at two-month intervals is significant ($p < .025$) with more than half the contribution to the χ^2 values coming from the excess of high values in October and November.

When seasonality is removed, the correlation between phytoplankton and radiolarians is significant ($\rho = 0.48$, $p < .001$) but explains only 23% of the variance of the ranked data. Correlation is maximal at a zero time lag. When radiolarians lag phytoplankton, there is a reason-

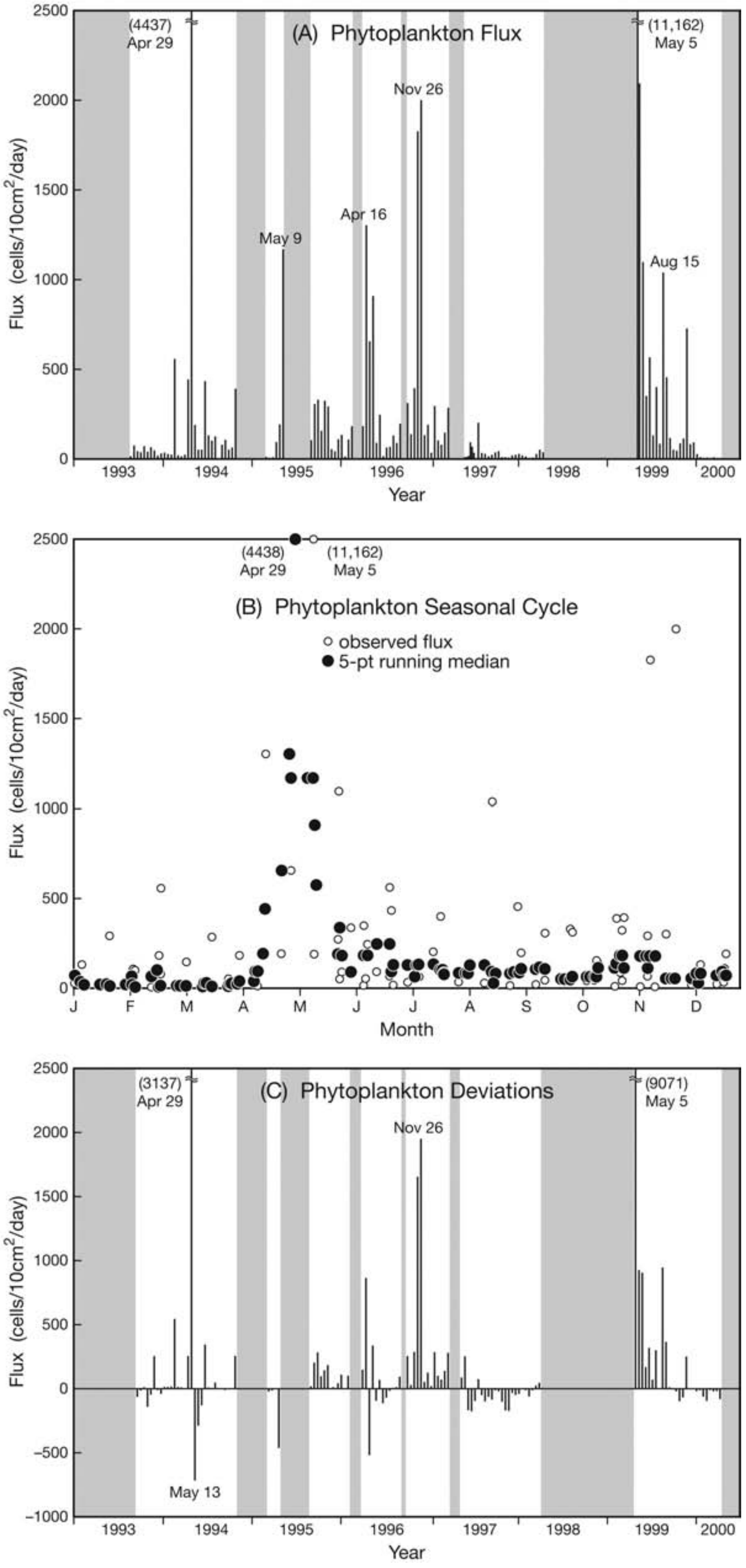

Fig. 6. Temporal patterns of siliceous phytoplankton flux. A) Flux measurements, 19 August 1993–12 April 2000. Shaded areas indicate the longer periods of missing sediment trap samples; B) Fluxes (open circles) and five-point running median (solid circles); C) Temporal distribution of deviations from seasonal model.

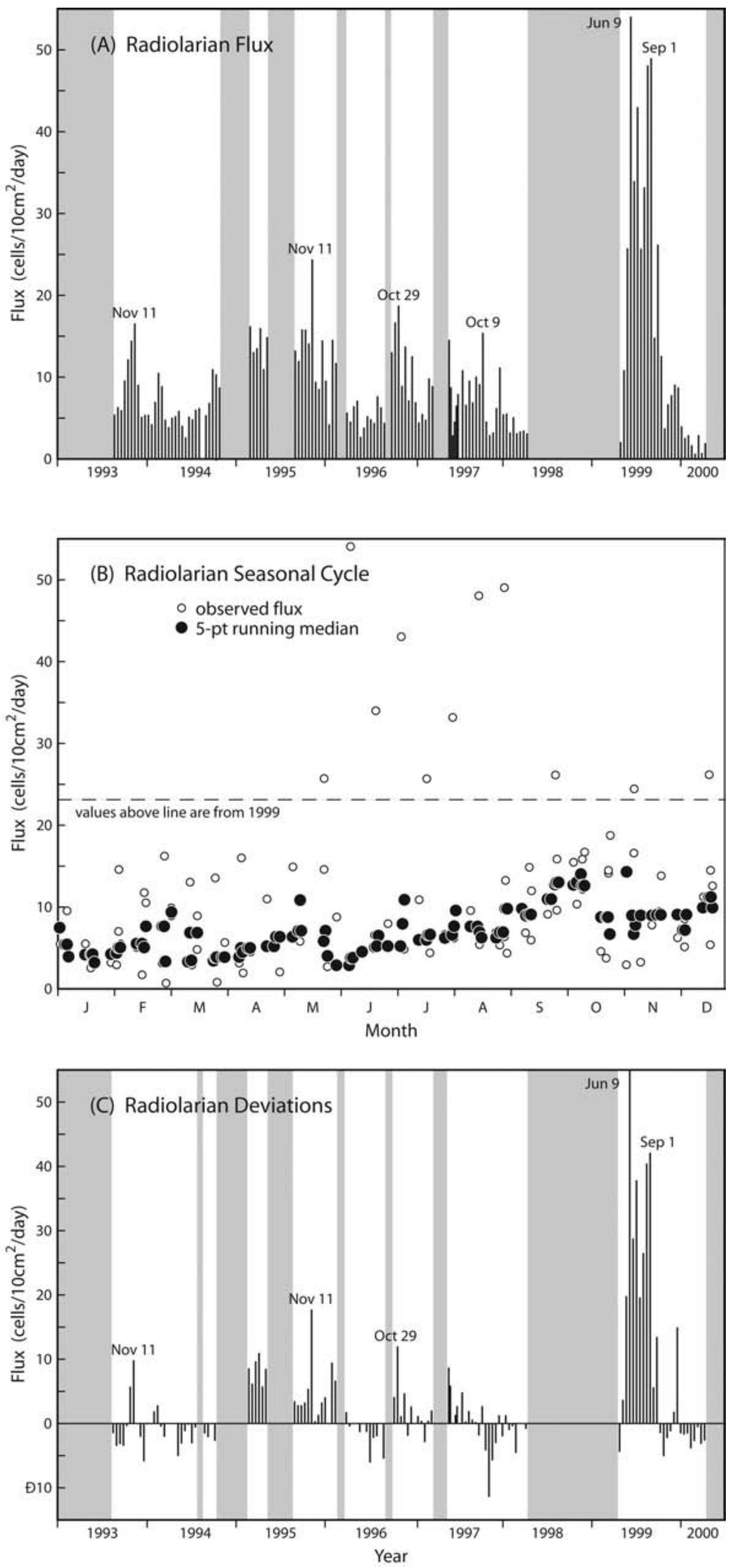

Fig. 7. Temporal patterns of radiolarian flux. A) Flux measurements, 19 August 1993–12 April 2000. Shaded areas indicate the longer periods of missing sediment trap samples; B) Fluxes (open circles) and five-point running median (solid circles). All values above the dashed line were observed in 1999; C) Temporal distribution of deviations from seasonal model.

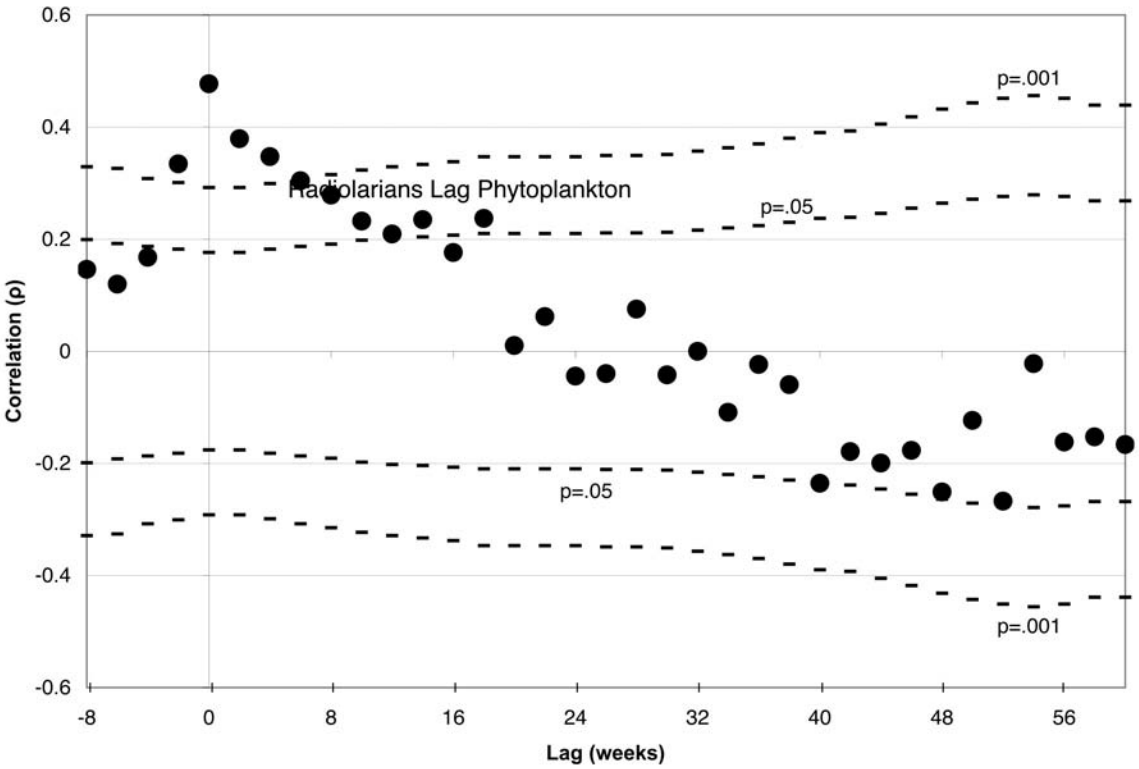

Fig. 8. Cross-correlation of siliceous phytoplankton flux and radiolarian flux, with radiolarians lagging phytoplankton. Negative lags indicate radiolarians leading phytoplankton. Input values are deviations from the seasonal models. "Confidence" bands, based upon changing degrees of freedom, are given as general references only.

able correlation within a 12-week window (fig. 8). A correlation at zero time lag is consistent with the shared variability imposed by the sampling procedure. However, the fact that the correlation persists for at least two months is less consistent with sampling artifact. Some similarities between phytoplankton and radiolarian fluxes are obvious, such as elevated fluxes of both groups in spring 1999 followed by low fluxes at the start of 2000 (fig. 6C, 7C). On the other hand, the prolonged periods of low flux of phytoplankton in March 1995 were not seen in the radiolarian flux, nor were the anomalously high phytoplankton fluxes in the fall of 1996. The high radiolarian fluxes in the summer of 1999 did not have a direct counterpart in the phytoplankton. Because fluxes of phytoplankton and of radiolarians may be at least partially responsive to different environmental parameters, the two data sets have been treated separately in the following analyses.

The Influence of Large-scale Forcing

When seasonality is removed from the parameters, the relationship between phytoplankton flux and climate is negative for a period of approximately 14 weeks (fig. 9A). Warm-water periods are related to reduced flux and cold-water periods to increased flux. Maximum negative correlation occurs at a lag of six weeks when about 10% of the flux variability is explained by the PDO.

Radiolarian flux also shows a negative response to changes in the PDO (fig. 9B). Maximum negative correlations occur at lags of between 38 and 52 weeks. At a 44-week lag time, changes in the PDO account for approximately 16% of the variability of radiolarian flux.

The Influence of Local Forcing

When seasonal variability is removed from parameters, the cross-correlations between phytoplankton flux and the magnitude of local circulation are negative (fig. 10A), indicating that equatorward flow is correlated with high flux and poleward flow with low flux. This is consistent with independent observations that higher phytoplankton biomass is advected into the SBC from upwelling regions along the central California coast while lower biomass is advected from the Southern California Bight (Otero 2002; Venrick et al. 2003). There is a sharp negative peak at three weeks that explains about 6% of the variability. The high-frequency variability of the correlogram is similar to the variability of circulation (fig. 4A, C), which suggests that circulation may account for some of the short-term variability in the flux data.

The relationship of radiolarian flux with circulation (fig. 10B) is similar to that of phytoplankton with respect to the high-frequency variability of the correlogram and

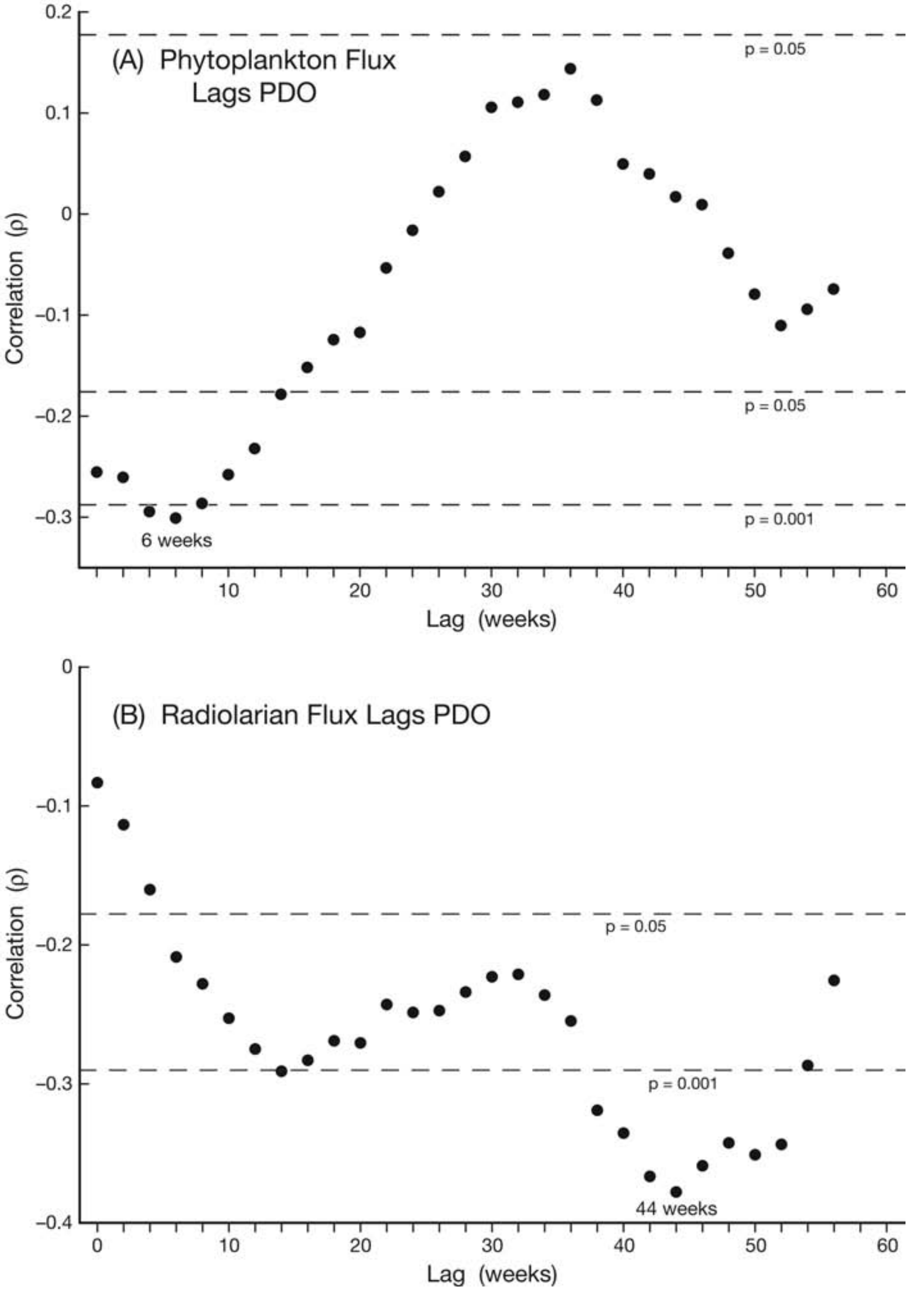

Fig 9. Cross-correlation of PDO and flux input values are deviations from seasonal means. "Confidence" bands, based upon changing degrees of freedom, are given as general references only. A) Siliceous phytoplankton flux; B) Radiolarian flux.

the general location of maxima and minima. However, there are no strong relationships between radiolarian flux and circulation at lags of less than 30 weeks. The strongest correlation, at a lag of 40 weeks, explains 12% of the flux variability.

Specific Events

To examine the influence on flux of extreme climate-driven events more directly, we have used the relationships indicated in the correlograms (fig. 9A and B) to define windows of response for siliceous phytoplankton and radiolarians. Phytoplankton flux has the strongest correlation with climate (negative ρ) when flux lags the PDO by 0–14 weeks. We thus define the window of response to be 0 weeks following the onset of extreme warm-water conditions (PDO deviation >1.62) or cold-water conditions (PDO deviation <-1.50) through 14 weeks (three months) following the end of these conditions. To examine phytoplankton flux during these periods we have plotted the flux data by month (fig. 11).

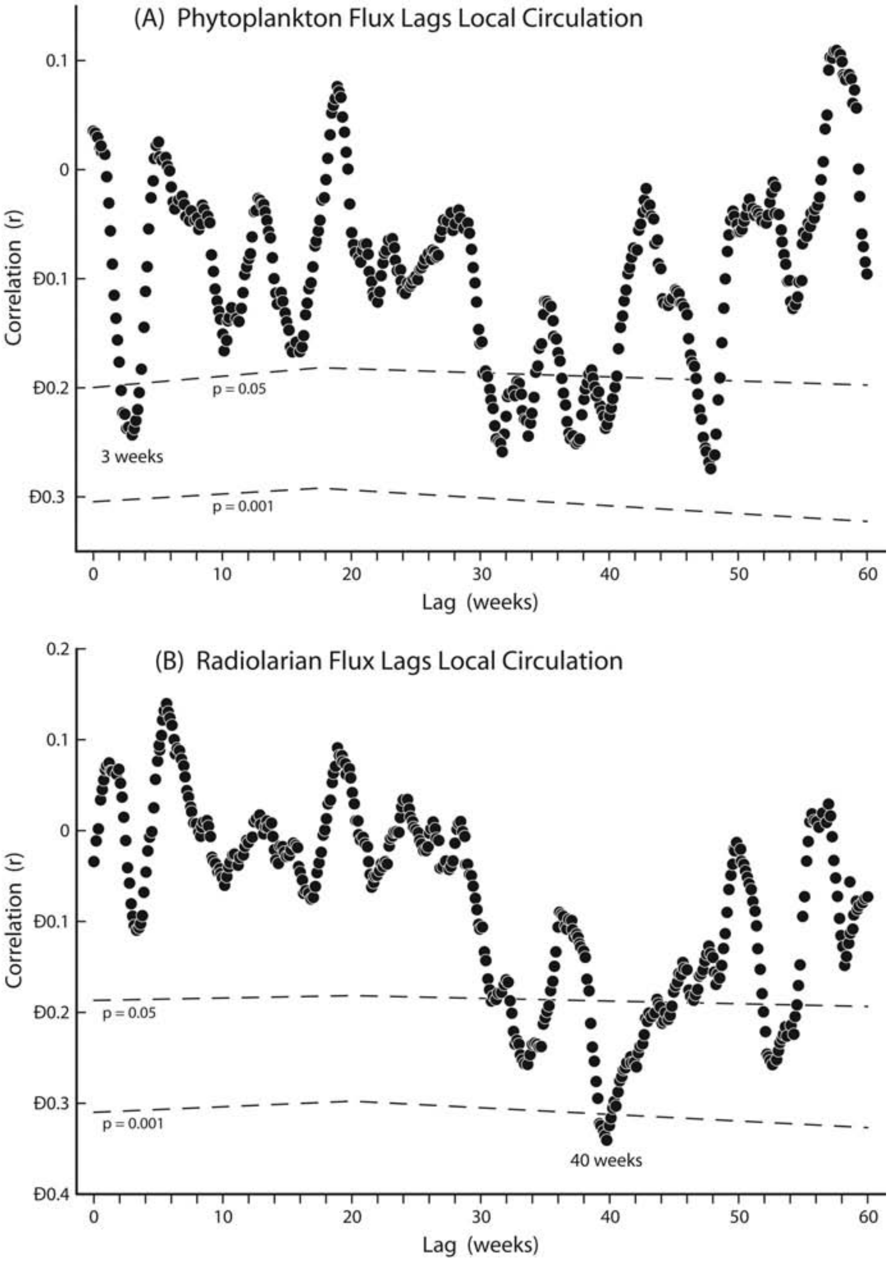

Fig 10. Cross-correlation of circulation (EOF #1) and flux, with flux lagging circulation. Input values are deviations from seasonal means. “Confidence” bands, based upon changing degrees of freedom, are given as general references only; A) Siliceous phytoplankton flux; B) Radiolarian flux.

Fluxes within the window of response to warm-water periods, such as 1993–94 (fig. 11A) and especially 1997–98 (fig. 11B), were the lowest summer and autumn fluxes seen during this study. This is consistent with the expectation of reduced flux during warm-water events. However, fluxes were not reduced during the entire window of response; they were above the monthly median in January 1994 (fig. 11A) when the response occurred early in the window, and were inconsistent in June–July (fig. 11B) when the response was somewhat delayed. Phytoplankton response to cold-water periods is less consistent (fig. 11C, D). The expected flux increases were not seen following the 1994 cold period. Fluxes in May through September 1999, following the large La Niña, were the highest observed in this study (fig. 11D). However, fluxes the following January–April 2000 (still partially in the window of response) were the lowest.

For radiolarians, the window of response is defined as 38–52 weeks (8–12 months) following the peak con-

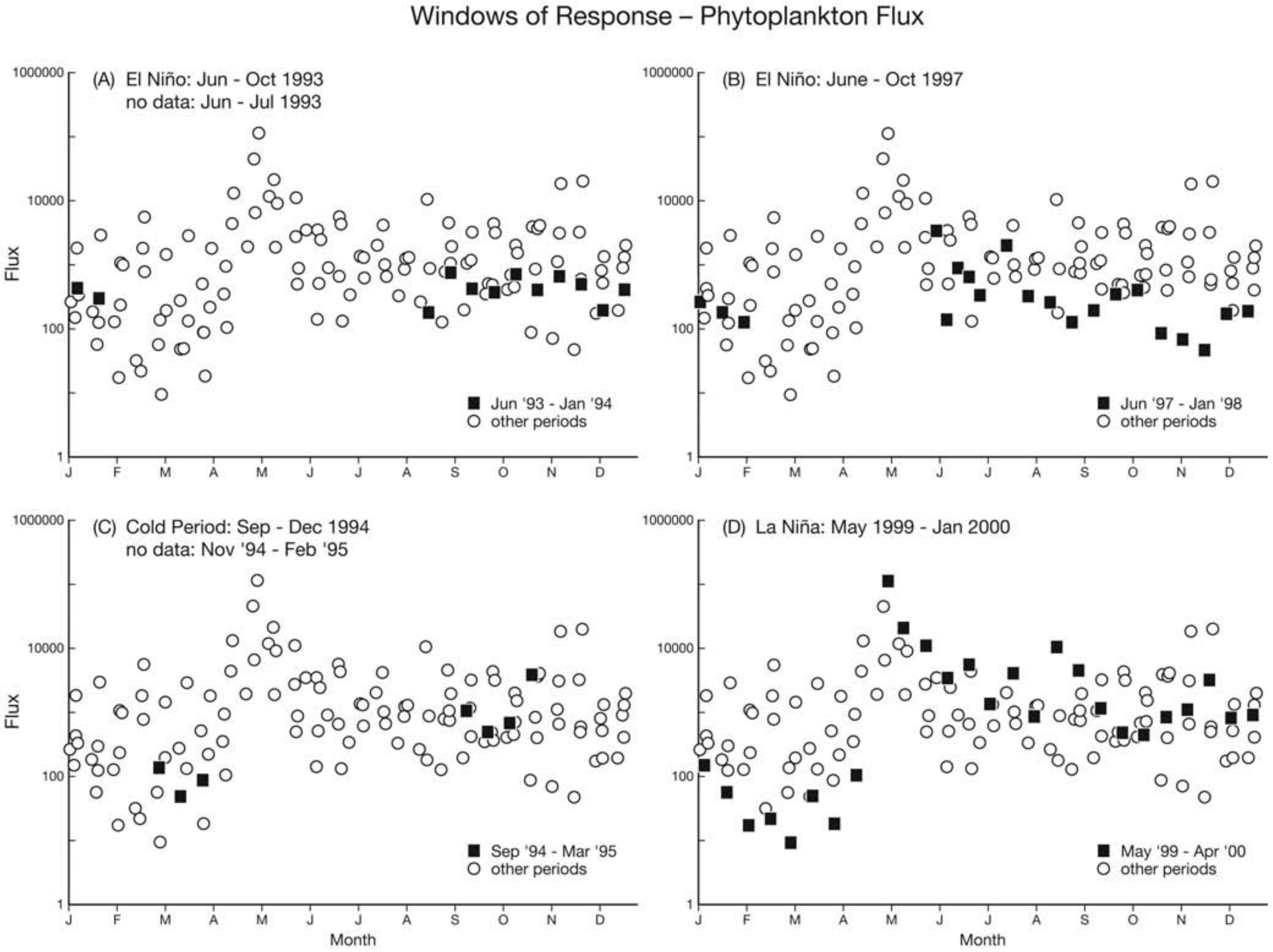

Fig 11. Response of siliceous phytoplankton flux to basin-wide warm- and cold-water events. Warm- and cold-water events are PDO deviations from seasonal model <−1.50 or >1.62; the timing of each event is given at the top left of each figure. On the basis of the cross-correlation of phytoplankton lagging PDO (fig. 9A), the window of response is defined as the onset of peak PDO through three months following the peak. The timing of each window is given in the legend. Fluxes within the window of response are indicated by solid symbols. A) El Niño event 1991–93; B) El Niño event 1997–98; C) Cold-water event of 1994; D) La Niña event of 1999.

ditions (fig. 12). The radiolarian response to warm water is less clear than that of phytoplankton. Fluxes in January–May 1994 appear to have been relatively unaffected (fig. 12A), but we are lacking samples during the latter part of that window. Fluxes in January–April, 1998, following the strong El Niño of 1997, were below the seasonal median (fig. 12B) but were not the lowest observed in those months.

Radiolarian fluxes following the 1994 cold-water event were only somewhat above the median (fig. 12C). Fluxes following the 1999 La Niña were, like phytoplankton fluxes, the lowest fluxes of the entire series at a time when the correlogram leads us to expect high flux. However, we are missing samples through much of this window and cannot rule out the possibility of a flux increase after our sampling ended.

These inconsistent and ambiguous responses to extreme events underscore the complexity of climate-ocean interactions and the inadequacy of condensing these into one or two indices. Several additional flux events were recorded that do not appear to be explained by the environmental factors under consideration:

1. The peak of phytoplankton flux in fall 1996 (fig. 6A, C). The concurrent PDO index (fig. 2) suggests a brief relaxation of generally warm-water conditions the previous August, and the EOF #1 of circulation (fig. 4) shows a reversal from a generally poleward flow in early October. Neither of these environmental changes seems extreme enough to explain the high-magnitude response of phytoplankton flux. On the other hand, chlorophyll concentrations in the euphotic zone around Point Conception recorded during the CalCOFI cruise that fall were anomalously high (Schwing et al. 1997). The elevated near-surface chlorophyll concentrations were not related to the local hydrographic conditions, although there was

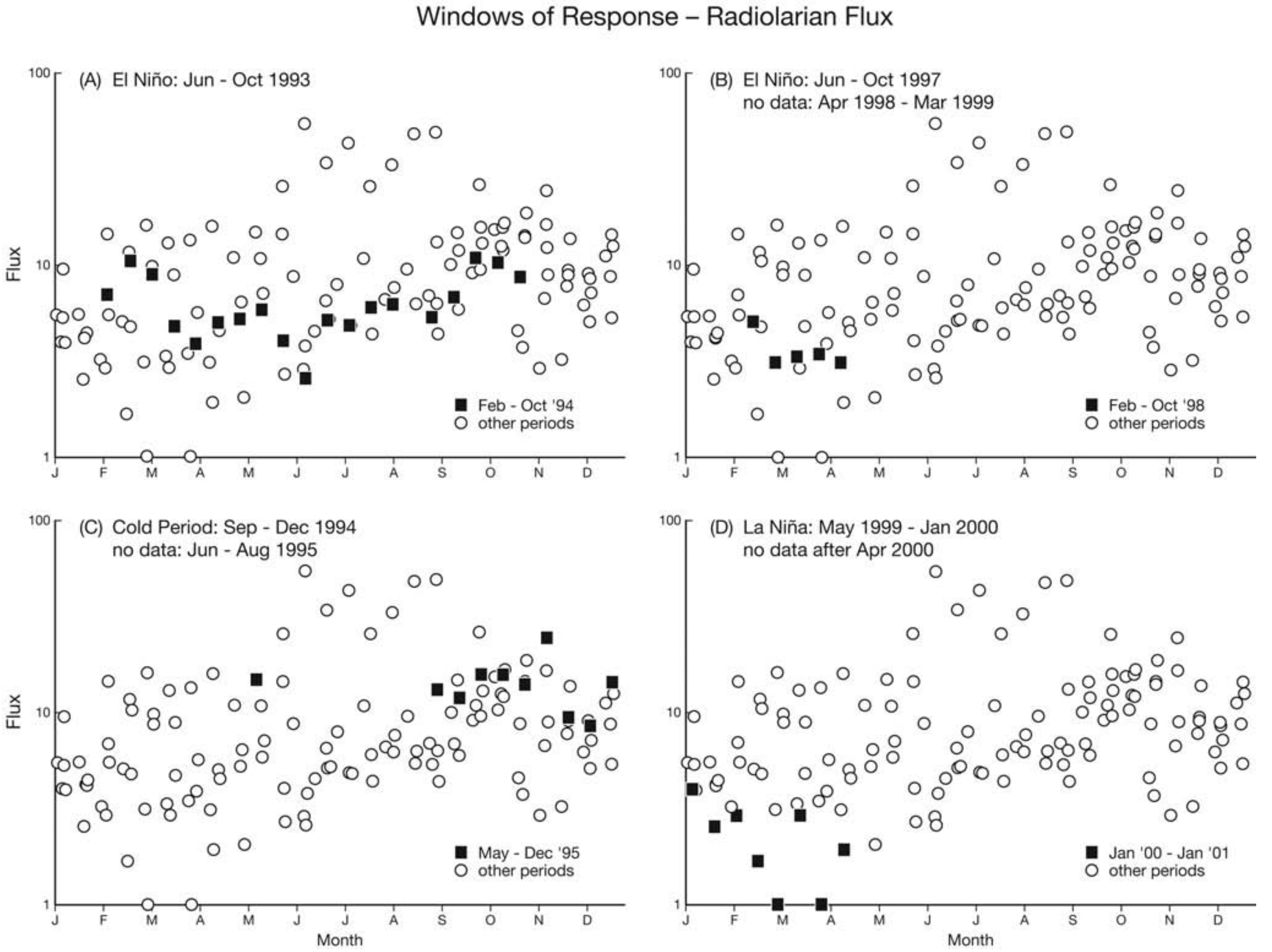

Fig 12. Response of radiolarian flux to basin-wide warm- and cold-water events. Explanation for Figure 11: On the basis of the cross-correlation of radiolarians lagging PDO (fig. 9B), the window of response is defined as 9–12 months after peak PDO deviations. A) El Niño event 1991–93; B) El Niño event 1997–98; C) Cold-water event of 1994; D) La Niña event of 1999.

some evidence for elevated upwelling north of Point Conception (Schwing et al. 1997). The trap data show no concurrent peak in radiolarian flux.

2. The very low fluxes of both phytoplankton and radiolarians during the final months of the trap series (January–April 2000; figs. 6A, C, 7A, C). January–March values were lower than the values associated with the previous El Niño. The previous PDO index and deviations were consistently negative (cold water), suggesting enhanced biomass.
3. The anomalous magnitude and pattern of radiolarian flux in 1999 (fig. 7A, C). Peak fluxes were not only double previous values, but occurred in late spring and summer instead of fall. These fluxes appear to be related to a very strong La Niña event, but peak fluxes followed the onset of cold water and preceded the peak La Niña event.

These periods of anomalous fluxes persisted for one to four months (2–10 trap samples). The explanation may be some unrecognized forcing mechanism, a confounding of recognized mechanisms, or non-linear responses of the microplankton to environmental variability. On a practical level, the duration of these anomalies defines the current effective resolution of the sedimentary record flux in the Santa Barbara Basin.

DISCUSSION AND CONCLUSIONS

The parameters investigated here are the total fluxes of siliceous phytoplankton, fluxes of radiolarians, climate (as indexed by the PDO), and local circulation (as indexed by the first EOF of near-surface circulation). Table 1 summarizes the major relationships. All parameters appear to have meaningful cross-correlations at some lag period. The positive correlation between phytoplankton and radiolarian fluxes with very short lag times (fig. 8) is not explained by a common response to either environmental variable considered here. Some fraction of this may be due to a sampling artifact.

TABLE 1

Characteristics of the correlograms presented in this paper. Values are the percent of variability accounted for. In parentheses are the lag times of the maximum correlations in weeks. Climatic influences are represented by the PDO, local influences by the first EOF of near-surface circulation. All data have been corrected for the annual cycle. Negative lag times indicate that the "lagging" parameter is leading.

	Lagging Parameter		
Leading parameter	local influences	phytoplankton flux	radiolarian flux
climatic influences	7% (−2) 8% (+2)	10% (6)	16% (44)
local influences		6% (3)	12% (40)
phytoplankton flux			23% (0)

For both phytoplankton and radiolarians, the shapes of the correlograms with climate and circulation are similar (figs. 9 and 10). For both groups, the strength of the relationship between flux and climate is somewhat greater than between flux and local circulation, but is expressed at somewhat greater lag times. Thus, phytoplankton flux lags the PDO by 6 weeks and circulation by 3 weeks, while radiolarians lag climate by 44 weeks and local circulation by 40 weeks. These results are consistent with an initial effect of climate on flux exerted through the effect of climate on circulation. This reinforcing of influences is also suggested by the correlation between climate and circulation (fig. 5), which peaks when circulation leads the PDO index. However, these two factors together explain less than 20% of the variability of fluxes of phytoplankton and radiolarians, even if climate and circulation act independently.

The high-frequency variability of both correlograms of flux with circulation (fig. 10) is much higher than that of flux with climate. This is not a function of the resolution of the data and is consistent with some direct influence of local circulation on the flux data. However, circulation patterns are so interrelated with climate that our limited flux data do not allow a clear separation of the signals.

Because much of the flux of siliceous phytoplankton appears to originate outside the SBC (Venrick et al. 2003) it is reasonable to postulate that changes in phytoplankton flux are a direct response to advection of different source populations, perhaps augmented by regional population growth in response to changes of wind-induced nutrient input. The response times of siliceous phytoplankton flux to both circulation and climate are consistent with this model. In contrast, the greatest correlation of radiolarians with both forcing scales occurs at unexpectedly long lag times. This suggests that the response of radiolarian flux is less direct. The most conservative interpretation is that radiolarian flux tends to be buffered from environmental changes, perhaps by the deeper distributions of many species, or their different trophic status. A detailed analysis of the radiolarian response is more appropriately conducted at the level of species, and will be deferred until our final paper.

All conclusions about the influence of climate patterns on fluxes are obviously complicated by the low number of "extreme events" that we sampled and by the gaps in our database. Thus, we sampled parts of two El Niño events and one La Niña event, but had a complete data set throughout our estimated window of response period for only radiolarian flux following the 1991–93 El Niño. We cannot eliminate the possibility that we missed the major responses. In general, the results indicate that patterns of biogenic flux are partially consistent with inter- and intra-annual changes in the regional oceanography. Patterns support the expectations that warm-water years and poleward circulation both favor reduced flux of phytoplankton and radiolarians. Evidence for enhanced flux during cold-water events is inconsistent.

A goal of this paper was to explore the resolution of the flux record by direct examination of the influence of local circulation patterns, which are known to have high frequency variability and are expected to influence flux by carrying microplankton from different environments. Our data indicate that with the present state of knowledge, about four months, or quarterly resolution, may be the appropriate limit of useful resolution. Clearly, a much longer data set and much greater understanding of causality are needed before we can accurately hindcast short-term events from sedimentary flux.

We emphasize that our seven-year data set, although too short to discriminate high-frequency forcing mechanisms in this study, is long relative to most sediment trap series. Our results must serve as a caution against over-interpreting sedimentary signals, and especially signals from observations over one or two years only.

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