Radiolarian Flux in the Santa Barbara Basin as an Index of Climate Variability

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ABSTRACT: Annual radiolarian flux (1954-1986) extrapolated from varved Santa Barbara Basin sediments was compared to instrumental data to examine the effect of interannual climate variability. Paleo-reconstructions over large geographic areas or 10^3 years and longer typically rely on changes in species composition to signal environment or climate shifts. In the relatively short period studied, climate fluctuations were insufficient to significantly alter the assemblage, but there was considerable variability in the total flux of radiolarians. This variability, greatest on 5- to 25-year time scales, appears to be linked to regional climate variability. Total flux correlates to regional California sea surface temperature and the composite of sea level pressure over the Northern Hemisphere for years of high radiolarian flux resembles positive PNA circulation.

Background

The effort to understand and model interdecadal to centennial-scale climate variability relies on development of high resolution climate proxies that extend farther back in time than the 100-year instrumental record. Such proxies are contained in sedimentary and other natural records (tree rings, corals, ice cores); however, high resolution records are relatively rare. Of the marine sedimentary records, that in the Santa Barbara Basin in the Southern California borderland is particularly useful for climate studies. Seasonal deposition in the basin is preserved in annual layers composed of couplets (varves) (Koide *et al* 1972) allowing for annual to subseasonal analysis. Additionally, the basin lies in the path of the California Current, whose properties are closely tied to climate (Norton *et al* 1985). Present-day teleconnections suggest that climate variability at Santa Barbara Basin is a sensitive indicator of broader-scale climate variability over the North Pacific/North American sector (Figure 1a, b).

Several microfossil records from Santa Barbara Basin have been used in climatic reconstructions (Kling 1977; Lange *et al* 1990; Baumgartner *et al* 1989; Weinheimer *et al* 1986). For example, at a resolution of 25 years Pisias (1978, 1979) used changes in radiolarian assemblages to reconstruct sea surface temperatures and dynamic heights for the past 8,000 years. These assemblages shifted synchronously with initiation of alpine glacial advances, on the order of 10^2-10^3 years. Annual geochemical and paleontological data from several Santa Barbara Basin cores spanning 50-200 years relate to deposition of varved and non-varved sections of the sediment and are considered to reflect climatic fluctuations (Schimmelmann *et al* 1992). Previous studies on annual time scales indicate that diatoms (Lange *et al* 1990) and fish scales (Baumgartner *et al* 1989) in the varves contain yearly-decadal variations indicative of some facets

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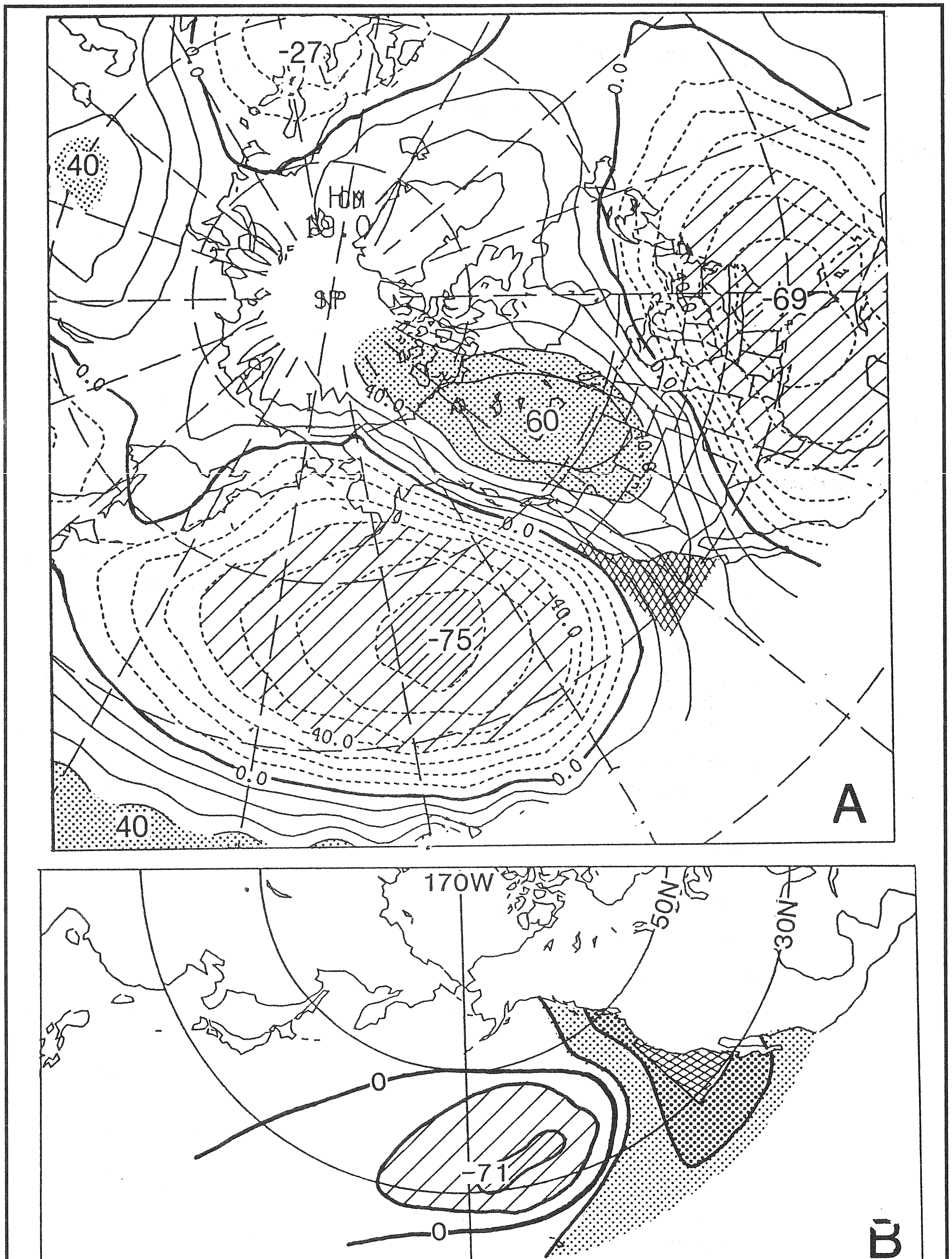

Figure 1. A. CORRELATIONS OF GRIDDED WINTER REGIONAL CALIFORNIA SST ANOMALIES (hatchured box) AGAINST 5° LATITUDE BY 10° LONGITUDE WINTER 700-MB HEIGHT ANOMALIES OVER THE NORTHERN HEMISPHERE.
B. CORRELATIONS (x 100) OF THE SAME SST ANOMALIES (hatchured box) AGAINST GRIDDED NORTH PACIFIC WINTER SST ANOMALIES.
Note the centers of action resulting from spatial coherence of sea surface temperature and pressure anomalies, as well as teleconnections over the North Pacific and North America.

of short-period climate variations. Also, radiolarian total and environmental group fluxes correspond to variability in the California Current, with higher fluxes during warm conditions (Weinheimer *et al* 1986). Even at much higher temporal resolution, on the order of weeks to months, available from sediment traps, variability in relative radiolarian species abundances has been related to seasonality of California Current flow (Welling *et al* 1992). The existence of interannual radiolarian fluctuations and their potential utility as climate proxies on a yearly scale warrants investigation of radiolarian flux in relation to interdecadal climate variability.

The period studied, 1954-1986, includes several climatic events that might be expected to affect radiolarian flux to Santa Barbara Basin. For instance, two major El Niños (1958-59 and 1983-84) and several smaller El Niños occurred during these years. Also, a major shift in Pacific climate occurred in the mid-1970s, affecting many systems (Ebbesmeyer *et al* 1991). These 30+ years seemed to contain enough interannual to interdecadal climate variability to further calibrate relative radiolarian species distributions as well as the total radiolarian flux against the instrumental record.

Methods

Sediment collected with a Soutar boxcore was retrieved from the center of Santa Barbara Basin at 580 meters depth. Thin slabs (1-2 centimeters thick) of the sediment were x-rayed, and contact prints of these were used to develop a chronology of the varves. The varves were dated independently by three investigators by counting the varves down from the top and comparing the varves to other previously dated cores. The three chronologies were within 1+/- years of each other. Varves dated 1954-1986 were individually sampled. These 33 samples were treated with hydrogen peroxide solution and hydrochloric acid, then sieved over a 45 μm screen. Quantitative slides of the larger than 45 μm fraction were counted for radiolarians (about 300 specimens per sample). All specimens were identified to the lowest possible taxonomic unit. Annual fluxes (no.$cm^{-2}yr^{-1}$) were extrapolated from the counts and surface area of the core. Potential error in subsampling of the varves was reduced by using 3-year averages of the fluxes.

Instrumental sea surface temperature data from six 5-degree squares along the California coast (Namias *et al* 1988) were averaged for an annual regional sea surface temperature time series. The salinity data are annual averages from La Jolla, California. The sea surface temperature and salinity data were smoothed with a 3-year running average. These two data sets were chosen over the CalCOFI data set for their continuity and frequency of observations.

Radiolarian Time Series

To estimate the effect of El Niño on the radiolarian flux, the annual total flux (no.cm^{-2}yr^{-1}) to the Santa Barbara Basin for El Niño and non-El Niño years can be compared (Figure 2a). The resulting time series does not show a consistent response to the El Niño events, though from previous work on a slightly different size fraction and time scale, there is some evidence for increased radiolarian flux during very strong El Niños (Casey *et al* 1989). A striking feature of the total radiolarian flux time series is its low-frequency signal.

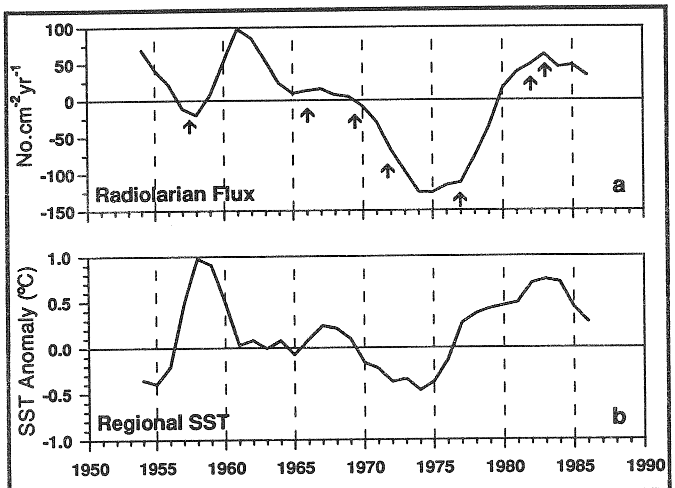

Figure 2. A. ANOMALOUS TOTAL ANNUAL RADIOLARIAN FLUX, 1954-1986, FROM SANTA BARBARA BASIN SEDIMENT.
B. ANOMALOUS REGIONAL ANNUAL SEA SURFACE TEMPERATURE (hatchured box, Figure 1).
Arrows indicate El Niño years. Both are 3-year running averages of annual anomalies.

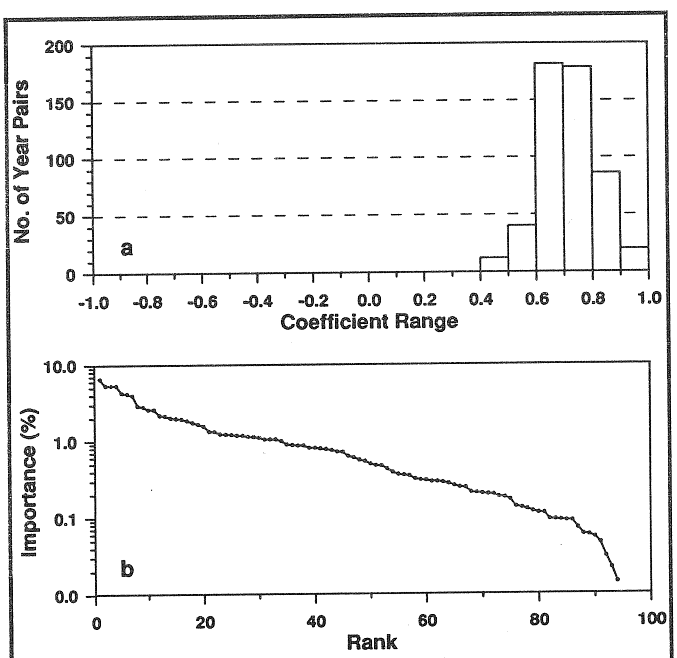

Figure 3. A. HISTOGRAM OF SPEARMAN RANK CORRELATION COEFFICIENTS OF SPECIES RANK COMPARISONS FOR ALL YEAR PAIRS, 1954-1986.
B. SPECIES IMPORTANCE AS MEASURED BY PERCENT OF TOTAL FLUX OVER ALL YEARS.

The flux of radiolarian tests into Santa Barbara Basin sediments is made up of species with different environmental preferences, so it is possible that their cumulative flux may reflect a regional climate influence. Time series of individual species flux were constructed to determine whether any species responded strongly to environmental conditions. These time series were quite similar to each other and to that of the total flux. To confirm and quantify this observation, the Spearman rank correlation coefficients for all possible pairs of years were calculated (Figure 3a). Spearman rank coefficients measure the similarity of relative abundance of pairs of variables (species). McGowan and Walker (1985) found that relative abundances of copepod species from the North Pacific were similar in tows taken within a province but showed significant differences between provinces. The generally high correlation coefficients for the Santa Barbara Basin radiolarians imply that the assemblage represents a population from one province. This is an interesting result, considering the heterogeneous nature of the California Current system and the occurrence of events such as the extraordinary 1982-83 El Niño.

Another important characteristic of the Santa Barbara Basin sediment's radiolarian assemblage is the stability over time of the cumulative distribution of species. Summing the species' relative abundance for all years and ranking them generates a log normal distribution (Figure 3b), with 13 species accounting for 50% of the cumulative distribution. The high coefficients, together with the log normal distribution, suggest that a few species consistently dominate the assemblage, few are rare, and many have intermediate abundances. This type of distribution characterizes species abundances in other single provinces (McGowan and Walker 1985; Hubbell 1979). The stable log normal species distribution implies that the radiolarian assemblage represents a single environment. The climate variability over the 3-decade study period apparently is not sufficient to significantly change the radiolarian assemblage, as it was over the past 8,000 years (Pisias 1979).

Comparison to Regional Sea Surface Temperature

Radiolarian flux during 1954-1986 to Santa Barbara Basin varies at a frequency similar to the 5- to 10-year periods that characterize the California Current (Chelton *et al* 1982). The state of the California Current, as represented by dynamic height and temperature data from the California Cooperative Fisheries Investigations (CalCOFI), has been related to sea surface temperature with low temperatures during strong southward transport and high temperatures with weak southward transport (Chelton *et al* 1982). Although the CalCOFI data set is the most complete of its kind, there are critical gaps, especially in the 1970s. Consequently, we use sea surface temperature determined from routine weather observations (ships and buoys, primarily; Namias *et al* 1988) as a proxy for California Current flow.

Interestingly, the radiolarian and sea surface temperature time series (Figure 2b) closely resemble each other, but with poorer fit at the beginning of the record (1954-1970, r=-0.30) than afterward (1970-1986, r=0.81). If the radiolarian time series is lagged 2 years with respect to sea surface temperature, the correlations improve (r=0.69 and 0.96, respectively). The correlation of sea surface temperature and radiolarian flux over the entire study period (r=0.49 at zero and 0.84 at 2-year lags) suggests that the two are related. If this connection is real, the relationship may be direct (*ie,* radiolarian flux is forced by temperature fluctuations) or it may be indirect (*ie,* both respond similarly to some common overall force). However, the offset of the flux and sea surface temperature in the first half of the record is large enough to warrant further investigation. A potential cause could be inaccuracies in dating the core, whereby if one or two years were not identified in the core, a given varve would appear to occur later (closer to the core top) and, hence, would lag its corresponding climatic match. We tried to avoid this type of error by having the core dated independently by three investigators, but it is possible that the same mistake is made repeatedly in dating the core.

Alternatively, a shift around 1970 in the biological response to external forcing relative to the sea surface temperature response could also produce the observed offset. For example, the mechanism(s) producing positively proportional sea surface temperature and flux (as in the later half of the time series) may be different to that creating the first half of the record when sea surface temperature and flux are not as well correlated. If this were the case, we could expect the physical mechanism forcing the sea surface temperature record to affect other physical aspects of the environment (*ie*, salinity).

In the region off California in the California Current system, the average salinity (1950-1978) decreases offshore and increases with depth; temperature increases offshore and decreases with depth; both increase southward along shore (Lynn *et al* 1982). (To the west of the California Current, in the North Pacific gyre, salinity increases to the west.) Consequently, under typical conditions, an increase in temperature should coincide with a decrease in salinity (in the area between the coast and the offshore salinity minimum of the California Current) and vice versa. Exceptions would perhaps include especially strong northward flow (El Niño) when an increase in temperature could be accompanied by an increase in salinity and, possibly, unusually strong southward flow with lower temperature and salinity.

Correlations and visual interpretations of scatter plots of the regional sea surface temperature and La Jolla salinity for the periods before and after 1970 (Figure 4a, b) show that temperature and salinity tend to vary inversely, and that there may have been a shift in the regime around 1970. Perhaps the higher correlation between sea surface temperature and salinity for 1970-1986 (r=-0.66) than 1954-1969 (r=-0.19) is evidence of a shift in the environment.

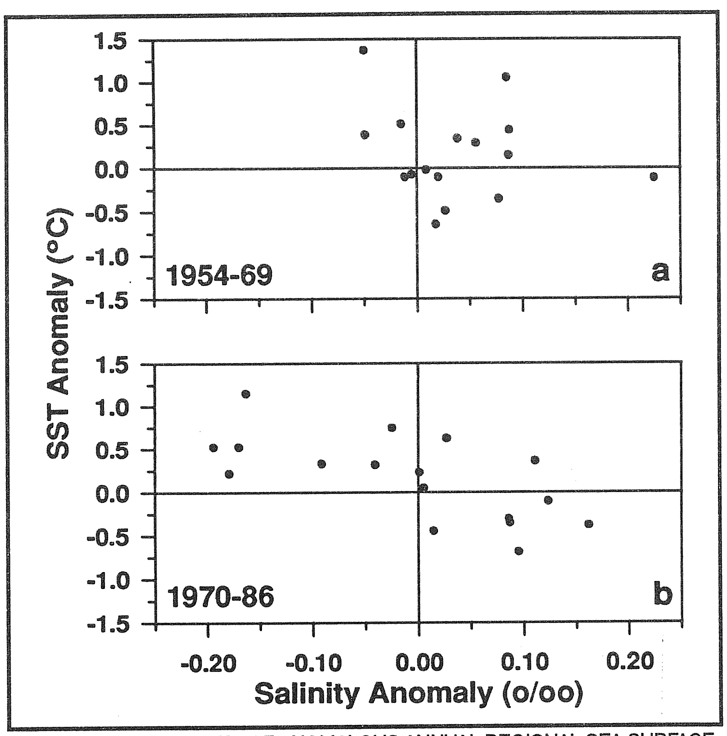

Figure 4. SCATTER PLOTS OF ANOMALOUS ANNUAL REGIONAL SEA SURFACE TEMPERATURE AND LA JOLLA SALINITY, 1954-1969 (A) AND 1970-1986 (B).

Although total radiolarian flux lags sea surface temperature, the possibility of the flux reflecting sea surface temperature still exists. If the radiolarian flux truly reflects sea surface temperature, what mechanism(s) produces this relationship and why is it apparently different from relationships linking sea surface temperature to other plankton groups? For example, low diatom (Lange *et al* 1990), foraminifera (Thunell and Sautter 1992), and zooplankton (Chelton *et al* 1982) abundances off California are associated with high sea surface temperature. Radiolarians differ from these groups in that they are relatively small heterotrophs (20-200 μm), omnivorous, and accept very small prey, including diatoms (Anderson 1983). Diatom cell size has been found to be related to nutrient distribution; generally decreasing in size with diminished nutrient concentration and patchiness (Turpin and Harrison 1980; Harrison and Turpin 1982; Harris 1986). It is conceivable that small heterotrophs are similarly adapted to low nutrient environments, characterized by less patchiness and small primary producers that would provide suitable prey. In the California Current system off northern California, Hood *et al* (1990, 1991) found small diatoms (<10 μm) predominant in the relatively warmer, lower salinity water, and less patchy chlorophyll *a* distribution seaward of colder, higher salinity water with larger, chain forming diatoms and patchier chlorophyll *a* distribution. The character of warmer water in the California Current system, lying seaward of upwelled waters, resembles an environment in which small heterotrophs such as radiolarians could thrive.

A possible hydrographic mechanism generating warm sea surface temperature and corresponding high radiolarian flux can be described as follows. Cooler sea surface temperature off the California coast occurs with enhanced southward transport and consequent upwelling. Conversely, warm sea surface temperature occurs when these transport mechanisms relax. This interpretation is consistent with the inverse relationship of coastal temperature and salinity observed. Considering that radiolarian density has been found to be low in water upwelled in the California Current system and to increase offshore (Gowing and Coale 1989), increased upwelling associated with offshore transport of upwelled water (Hood *et al* 1990), incorporates more radiolarian-poor, cool, high-salinity water into the California Current system; whereas, diminished upwelling associated with onshore movement of the California Current brings radiolarian-rich, warmer, low-salinity water into Santa Barbara Basin.

Such a scenario of strong southerly flow with offshore transport of upwelled water in contrast to diminished southerly flow with onshore movement of the California Current can explain the observed relationships between sea surface temperature, salinity, and radiolarian flux. During periods of upwelling, cold, high-salinity water with low radiolarian content is incorporated into the California Current system via filaments and eddies (Hood *et al* 1990). As southward transport and upwelling decrease, the California Current moves inshore and brings warm, low-salinity water with high radiolarian content into Santa Barbara Basin.

Radiolarian Flux-Regional Climate Relationship

The correlation of radiolarian flux to regional sea surface temperature fluctuations suggests that the flux is related to large-scale atmospheric circulation. One indicator of circulation in the region is sea level pressure over the North Pacific and western North America sector. A predominant mode of variability in sea level pressure over the North Pacific consists of two clusters of anomalies that are out of phase with each other; one along the west coast and the other over the central North Pacific (Figure 1a).

The seasonal sea surface temperature anomaly exhibits a similar pattern (Davis 1976) (Figure 1b). The circulation pattern characterized by a strengthened North Pacific subtropical high, deepened Aleutian low, and strengthened high over western Canada-Pacific Northwest is referred to as positive Pacific/North American pattern (PNA) (Wallace and Gutzler 1981). A regional effect of positive PNA is warmer temperatures off the California coast, possibly resulting from an increase in warm water entering from the south and west and diminished input of cool subarctic water from the north (Norton *et al* 1985).

The composite winter sea level pressure anomaly over the Northern Hemisphere for the 12 years of highest radiolarian flux (Figure 5) exhibits a well-developed Aleutian low and a high pressure center over the Pacific Northwest. This pattern of sea level pressure resembles the deep Aleutian low phase of PNA circulation suggesting that the PNA can be extracted from radiolarian data.

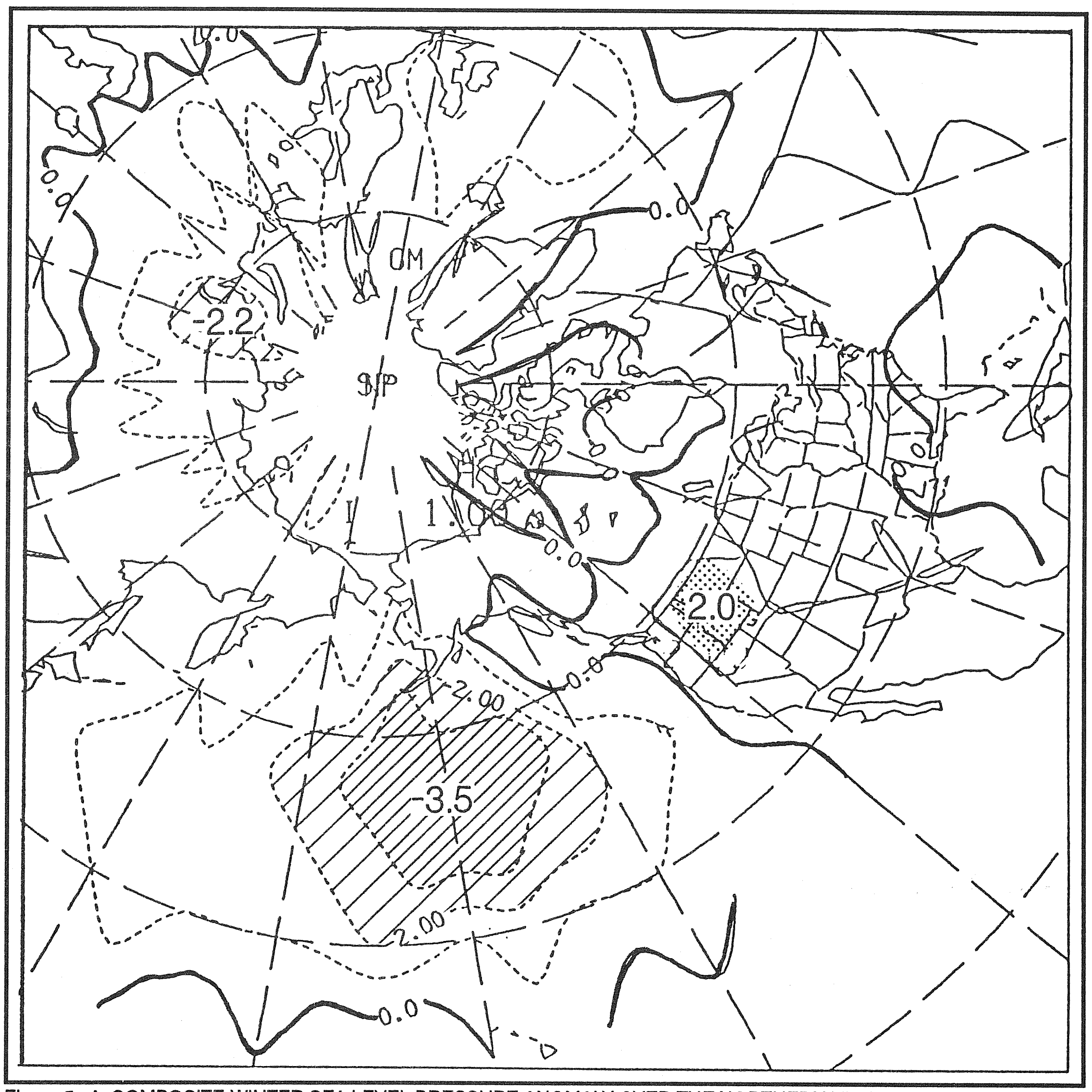

Figure 5. A. COMPOSITE WINTER SEA LEVEL PRESSURE ANOMALY OVER THE NORTHERN HEMISPHERE FOR THE 12 YEARS OF HIGHEST RADIOLARIAN FLUX, 1954-1986.
The deep Aleutian low over the North Pacific and high pressure center over the Pacific Northwest resembles positive PNA circulation.

The negative mode of PNA, typified by an Aleutian high and lows where highs exist in the positive PNA, is associated with cool temperatures along the California coast. Cross-correlations of the total radiolarian flux and sea level pressure do not generate this phase of PNA.

Conclusions

The radiolarian assemblage preserved in Santa Barbara Basin sediment exhibits an organization resembling that of other plankton groups within single provinces. A Spearman rank correlation indicates that the climate variability during 1954-1986 was large enough to slightly alter the mix of dominance within this province, but this is less than would be expected if there were an alternation of multiple assemblages from surrounding provinces. Apparently, the Spearman rank analysis is not sensitive to potential, but more subtle, changes due to interannual-decadal scale environmental change. Because none of the species consistently becomes rarer through time, it is likely that post-deposition alteration of the assemblage is negligible.

Comparison of radiolarian flux with environmental variables suggests that flux is related to sea surface temperature and salinity in the California Current system. These time series closely resemble each other, varying at a low-frequency decadal scale. However, there are some differences between the period before about 1970 and afterward. For instance, the radiolarian record is offset from sea surface temperature and the inverse relationship between annual coastal sea surface temperature and salinity is less well defined before 1970 than in the years following. Correlation between radiolarian flux and sea surface temperature peaks at flux lagging sea surface temperature by 2 years, which is perplexing because of the short radiolarian life cycle and their rapid sinking rates. The lag may reflect a biological response to environmental conditions before 1970 that differed from those after 1970, though an error in the chronology may also contribute to the lag. Inspection of radiolarian environmental group and individual species fluxes may reveal finer-scale variability relating to the apparent change around 1970, which may help in understanding the 1970 transition. Further, different cores will be sampled to test whether the chronology and the shift in response are consistent.

The association between increased total radiolarian flux and increased temperature may be explained by considering radiolarian environmental adaptations and their horizontal and vertical distributions. Radiolarians are adapted to environments with small primary producers and reduced patchiness, as occurs in the warmer water of the California Current system (Hood *et al* 1991). Additionally, the distribution of radiolarian abundance and temperature increase offshore, while salinity decreases; onshore-offshore shifts of the California Current system would lead to increased radiolarian abundance with increased temperature and decreased coastal salinity. This is consistent with the atmospheric circulation composite, which shows that a positive PNA-type circulation corresponds to high radiolarian flux and high sea surface temperatures along the California coast.

Initial analysis of the recent 30+ year portion of the available Santa Barbara Basin radiolarian record indicates that regional-basin scale variability of yearly climate can be retrieved from this time series. To verify and further elucidate this relationship, a time series spanning the instrumental record (about the last 100 years) must be developed and tested to determine whether the relationship of the radiolarian flux to sea surface temperature and sea level pressure presented here are maintained. If this test is successful, then a much longer (at least 2000-year) Santa Barbara Basin record can be exploited.

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