Variability in a Radiolarian Time Series and Its Relationship to Climate

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Abstract: Recently, paleoceanographers have been challenged to produce reliable proxies of climate variables that can be incorporated into climate models. In developing proxies using time series of annual radiolarian species fluxes from Santa Barbara Basin, we identify groups of species associated with years of extreme sea surface temperatures and sea level heights. The relative fluxes of warm and cool species are generally inversely related in 1914-1991 and fairly reliably reflect SST in 1955-1991. However, these groups do not reflect SST in 1914-1954, even though their fluxes continued to be inversely related. Species associated with high and low sea level height exhibit a similar pattern. Analysis of species structure indicates variability within the system and no evidence of assemblages from surrounding provinces dominating the species structure at any time. Failure of the proxies in 1914-1954 may be due to changes within the California Current System or in the biologic response to hydrographic conditions, or it may indicate a problem with our chronology of the varves.

Predicting climate and climate change through modeling is important to both science and economics. Climate varies over time scales of years to centuries and can shift abruptly or change gradually. Low frequency changes over the past century have been attributed to both anthropogenic effects and to natural variability of the climate system (Bloomfield and Nychka 1992; Keeling *et al* 1992; Wigley and Raper 1990). To separate these sources of observed change, we need to know magnitude and frequency of natural climate variability. However, instrumental records are short relative to the important time scales of variability (decadal-century; Bloomfield and Nychka 1992). Instrumental records used to develop and validate climate models span, at most, 150 years. One way to extend instrumental records and provide time series for validation of models is to use natural records (*ie,* tree rings, ice cores, corals, sediment). These longer records also contain a history of the full range of climate variability, with several realizations of decade and longer scale changes not available in instrumental records. Until we have records with sufficient realizations of this variability, our understanding of the causes of climate change is limited.

Over the past century, global temperatures have been increasing. Initiation of this "global warming" coincides with the industrial revolution, prompting the hypothesis of the greenhouse effect. Alternatively, the warming may be an expression of low frequency, natural variability. To separate natural and anthropogenic effects, we need a history of climate prior to instrumental records with which we can put changes of the past century into context with respect to natural variability. Extending the

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instrumental records with the marine record can be done mainly with corals or sediment. Reconstructions of temperature and salinity from corals have been successful (Dunbar *et al* 1994; Linsley *et al* 1994). However, large, long-lived corals used in paleoclimate reconstructions are restricted to tropical latitudes, and a major source of climate forcing is in the mid-latitudes (Latif and Barnett 1994).

Environmental conditions are also recorded continuously in marine sediments. Ideally, with seasonal deposition of sediment and low oxygen bottom waters, annual layers of sediment are preserved. These conditions exist in the Santa Barbara Basin in the Southern California Borderland (Koide *et al* 1972; Soutar and Crill 1977). Annual laminations are preserved in this sediment throughout the Holocene (Kennett, Baldauf, *et al* 1994). Seasonal runoff of terrigenous material during winter, alternating with biogenic siliceous material in spring and summer, generates a layered pattern in the sediment. These varves (one year of sediment composed of one dark and one light layer) are preserved because the low oxygen water entering the basin excludes burrowing animals from the bottom of the basin. In addition to its ideal depositional environment, the geographic location of Santa Barbara Basin lies at a center of action for both oceanic and atmospheric circulation patterns (Davis 1976). Cross correlations of California regional sea surface temperatures with North Pacific SST and Northern Hemisphere 700mb heights show coherence and teleconnections between Santa Barbara Basin and the North Pacific Basin and North America.

There has been some debate over how well records from Santa Barbara Basin represent the California Current. However, several studies show that these records reflect basinwide oceanic and atmospheric conditions (Miller *et al* 1994; Lange *et al* 1990; Weinheimer and Cayan 1994). In fact, recent results from the longest cores taken in Santa Barbara Basin, those of the Ocean Drilling Program, suggest that paleoceanographic changes over the past 20ky in the basin are linked, probably by atmospheric coupling, to similar events in the Atlantic Ocean (Kennett and Ingram 1995). There is strong evidence that its sedimentary record contains multiple proxies of Pacific-wide fluctuations in oceanic and atmospheric conditions (Pisias 1979; Lange *et al* 1990; Weinheimer 1994). In this region, changes in oceanic circulation and water masses strongly influence SSTs, planktonic assemblages and productivity (Lange *et al* 1990; Pisias 1978). Typically, during periods of high sea level pressure over the Central North Pacific, southward flow of the California Current is strong, resulting in low SST, low sea level height (SLH), high productivity, and cool water planktonic assemblages in Santa Barbara Basin. These conditions reverse with low pressure over the Central North Pacific. Results presented here are the latest in developing the radiolarian component in the Santa Barbara Basin sediment as proxies of instrumental records used in measuring climate-induced fluctuations in the California Current.

Methods

Varved sediments in the Santa Barbara Basin were collected by boxcore (SBBC 9110 1302-2; 34°12.9'N, 120°03.2'W, 588m). A vertical slab of the boxcore was sampled at annual resolution using a contact print of an x-radiograph as a template, and the surface area of each annual sample measured. The >45 µm siliceous fraction was extracted, and a known volume was analyzed for radiolarians, identifying 300-500 specimens, per year. Annual accumulation rates (no.cm^{-2} y^{-1}) were calculated for the total radiolarian assemblage (Figure 1) and for each species from 1914 to 1991.

We developed a different approach in grouping species into climatically indicative units than we have used in the past. Previously, we grouped species according to their water mass affinity (*ie,* Weinheimer and Cayan 1994). Although these "environmental" groups reflected regional to hemisphere scale climatology, we wanted more objective definitions of the groups. Since we know radiolarians with cold and warm affinities are found in Santa Barbara Basin sediment, we chose two instrumental records reflecting cold and warm conditions in the California Current System (SST and SLH) to compare to species accumulation rates. We used annually averaged, 5-degree-gridded monthly mean SST from 30-40°N, 135-120°W (Parker and Jackson 1995), to derive the annual regional SST time series. The sea level height record is a composite of annually averaged Los Angeles monthly detrended sea level height (1924-1991) from the Permanent Service for Mean Sea Level dataset and annually averaged San Francisco monthly sea level height (1914-1923) in Cayan *et al* (1991). Although these records have monthly resolution,

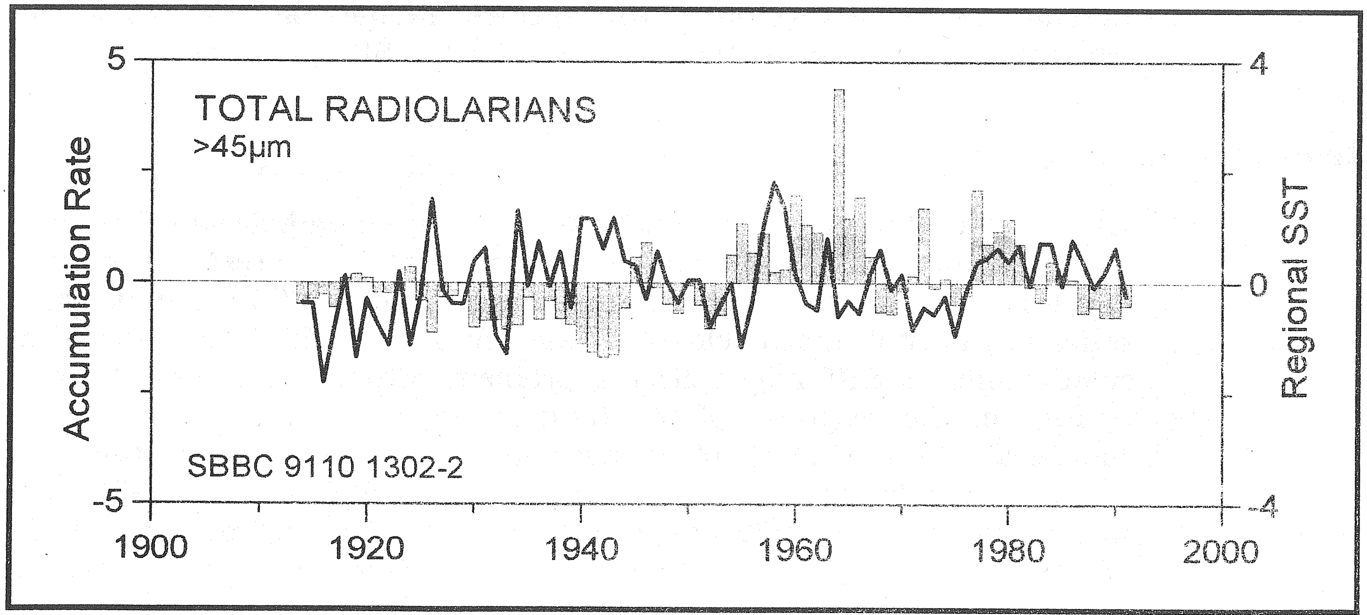

Figure 1 Annual accumulation rate of total radiolarians (bars), 1914-1991, and regional annual SST (solid line), 1900-1991. Both time series are shown as standard anomalies taken over the period illustrated.

we chose to annually average them to match the scale of resolution available in the sedimentary record. Whether the deposition of radiolarians in the Santa Barbara Basin is episodic, occurring within one season or another, as in diatoms (Grimm *et al* in press) is not presently known. Half of the time series was used to develop these proxies (1955-1991) and the other half for validation (1914-1954). Species associated with warm SST were identified by comparing, using t-tests, their average flux for the 12 years with the warmest winter SSTs in 1955-1991 to their average flux in the balance of the years between 1955 and 1991. Similarly, species associated with cool SSTs were identified in the 12 coolest winters. Four categories of species resulted: category 1 contains species with higher flux in the 12 years with the warmest winters; category 2 contains species with lower flux in the 12 years of warmest winters; category 3 contains species with higher flux in 12 years of coolest winters; and category 4 contains species having lower flux in the 12 years of coolest winters. This procedure was repeated for spring, summer, and fall. We summed the accumulation rates for species with similar responses to SST (*ie*, species with higher fluxes in years with warmest seasons, *etc*) to generate the four time series in Figure 2; the same was done for SLH (Figure 3). No species is represented more than once in the paired SST or SLH time series.

Conceivably, a cosmopolitan type species might have high flux during both cool and warm years. Although a few species, for example, had high fluxes in years with warm season(s) and low fluxes in years with cool season(s), only one species exhibited high fluxes for both warm and cool years. This species was not included in further analyses. No species was associated with both high and low SLH. In cases in which a species had high flux in years of warm (cool) seasons and low flux in years of cool (warm) seasons, it was grouped with species that had high fluxes in warm (cool) years. The same method was used for the SLH groups.

Results

As a first evaluation of the relationship between radiolarian flux and hydrographic conditions, we compared the total flux to regional annual SST (Figure 1). Decadal trends in flux and SST after 1950 resemble each other but do not appear closely related prior to 1950. This change in relationship to SST may reflect a problem with our chronology or a change in the response of the radiolarians to SST. If the cause is biological, then evidence of change, such as in the species present, should coincide with the shift in response to SST around 1950. We investigated the possibility of a biological effect using the Spearman rank correlation (Sokal and Rolf 1969) to measure interannual similarities in assemblages.

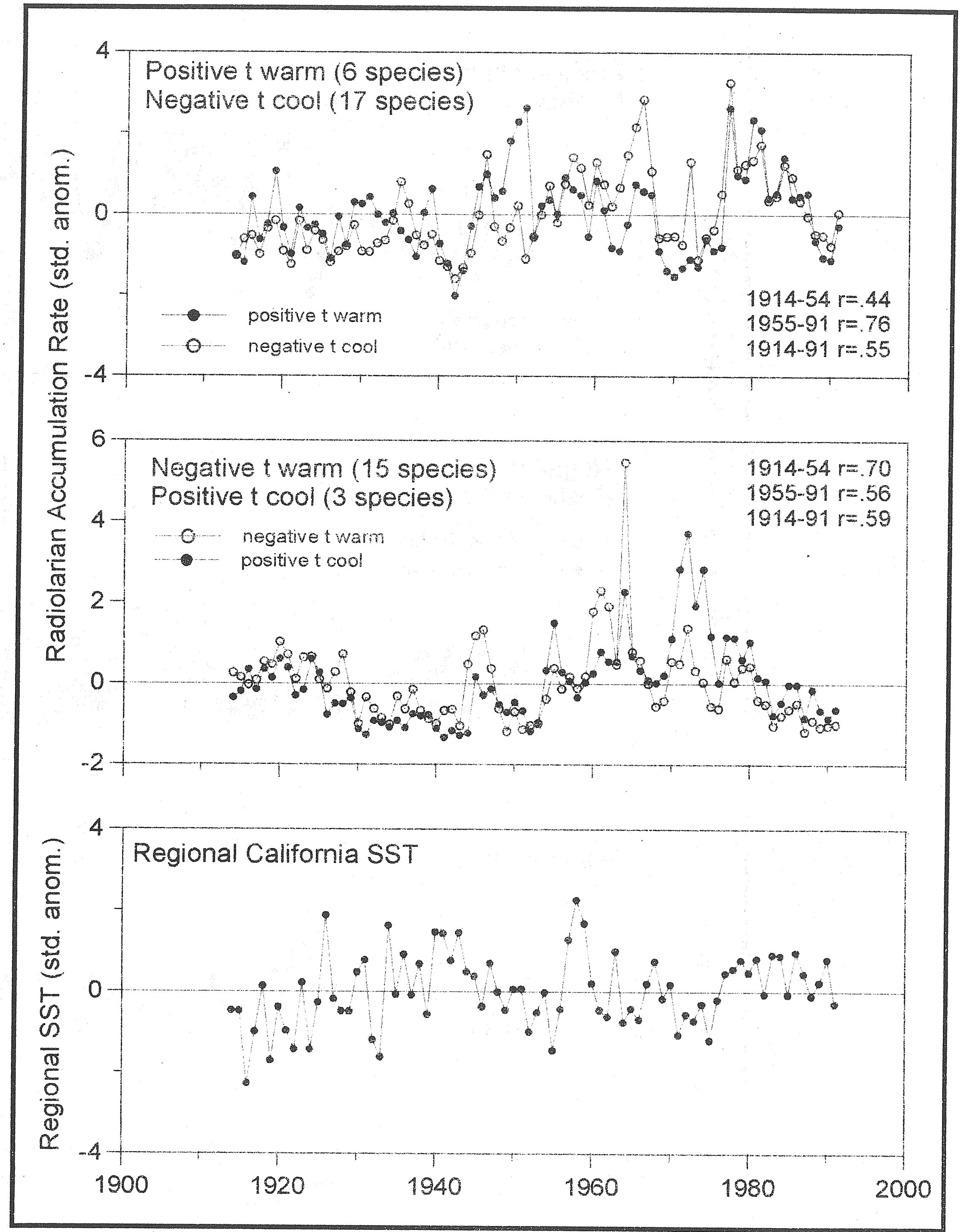

Figure 2 Accumulation rates of species with significant fluxes during warm or cool years. Top panel shows the sum accumulation rate of "warm" species with higher fluxes during warm years (positive t warm) and with lower fluxes in cool years (negative t cool). Middle panel shows the sum accumulation rate of "cool" species with lower fluxes during warm years (negative t warm) and higher fluxes during cool years (positive t cool). The number of species comprising each time series is in parentheses and correlation coefficients for each pair of time series is in the respective panel. SST is in the bottom panel. All data are standard anomalies calculated over the period illustrated.

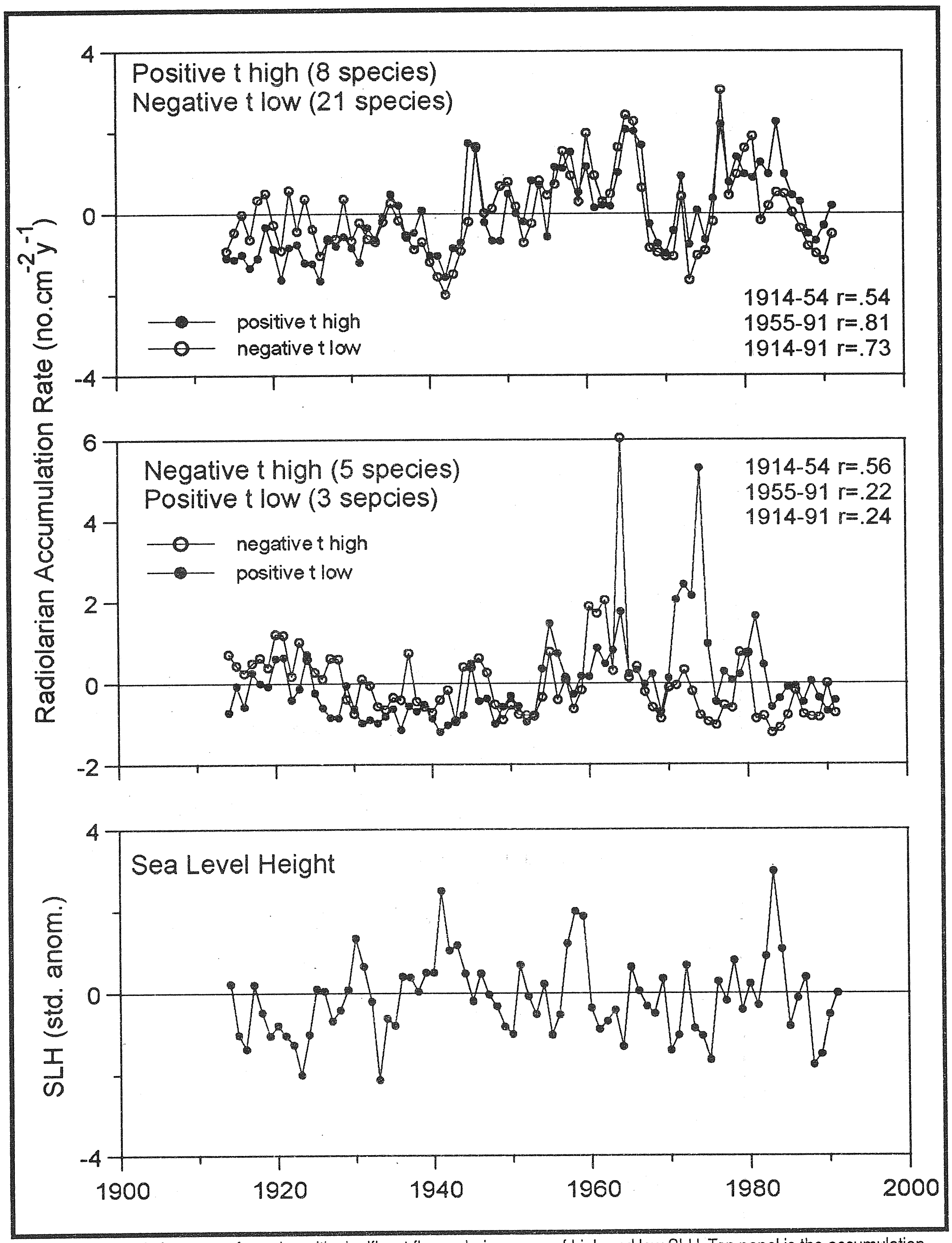

Figure 3 Accumulation rates of species with significant fluxes during years of high and low SLH. Top panel is the accumulation rate for "high" sea level species with higher fluxes in high SLH years (positive t high) and lower fluxes in low SLH years (negative t low). Middle panel shows the accumulation rate for low, SLH species with lower fluxes in high SLH years (negative t high) and higher fluxes in low SLH years (positive t low). The number of species used in each time series is in parenthesis and correlation coefficients between pairs are listed in both panels. SLH in the bottom panel is a composite of San Francisco (1914-1923) and Los Angeles (1924-1991) SLHs. All data are standard anomalies calculated over the period illustrated.

Species Structure

Consistency in species structure over a geographic region can be used to delimit oceanic ecosystems (McGowan and Walker 1985). Conversely, change in species structure over time or space can indicate a geographic shift in a boundary in time or transgression of a boundary in space. As a measure of species structure, we used the Spearman rank correlation (Sokal and Rolf 1969) of species abundance where a rank of 1 indicates identical species rank structure, 0 indicates no similarity, and –1 indicates inverse structure. The average coefficient for each year (Figure 4) ranged from r=0.51-0.87 (mean=0.83, r significant at 95%=0.251). Although there was some interannual variability in species structure, the correlations suggest no major shift in species structure. Years with lower coefficients tended to be associated with El Niño and warm years (1942, 1943, 1957, 1965, 1986) and, generally, years in the second half of the time series had slightly lower average coefficients than the first half. This suggests that faunas from different provinces may have been introduced to the California Current system during El Niño or warm events, and also perhaps more frequently since the 1950s.

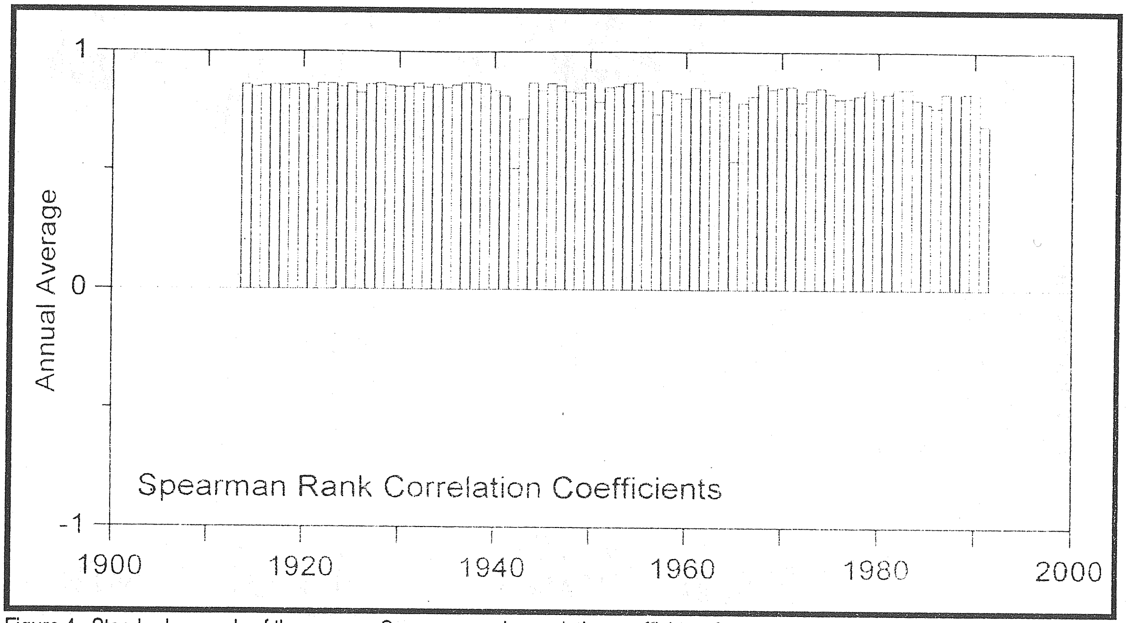

Figure 4 Standard anomaly of the average Spearman rank correlation coefficients for each year in the time series.

Class Accumulation Rates

The high correlation between series in each pair illustrated in Figures 2 and 3 shows, for example, that species with warm affinities (low flux during cool years or high flux during warm years) respond similarly to environmental conditions. Correlations for 1914-1954 are generally as high as for 1955-1991, indicating that the species in each pair of series represents a coherent unit. Since the series in each pair are so similar, we summed their ARs to form four classes: warm and cool based on SST and high and low based on SLH.

Class Percents

An obvious feature of the percent warm and cool class time series (Figures 5 and 6) is their inverse relationship, maintained in both the developmental (1955-1991, r = -0.77) and independent (1914-1954, r = -0.89) periods. The SLH classes are also inversely related but not as dramatically (r = -0.69 and -0.76, respectively). Even though the warm and cool classes were defined using extreme SSTs, the correlations with SST generally are not significant, with percent cool correlating better to SST than percent warm (Table 1). The percents of high and low SLH class also correlate poorly to the instrumental SLH record. Interestingly, not only do the SST and SLH classes validate, in spite of their lack of agreement to instrumental records, but the SST classes are more disparate in 1914-1954 than in 1955-1991.

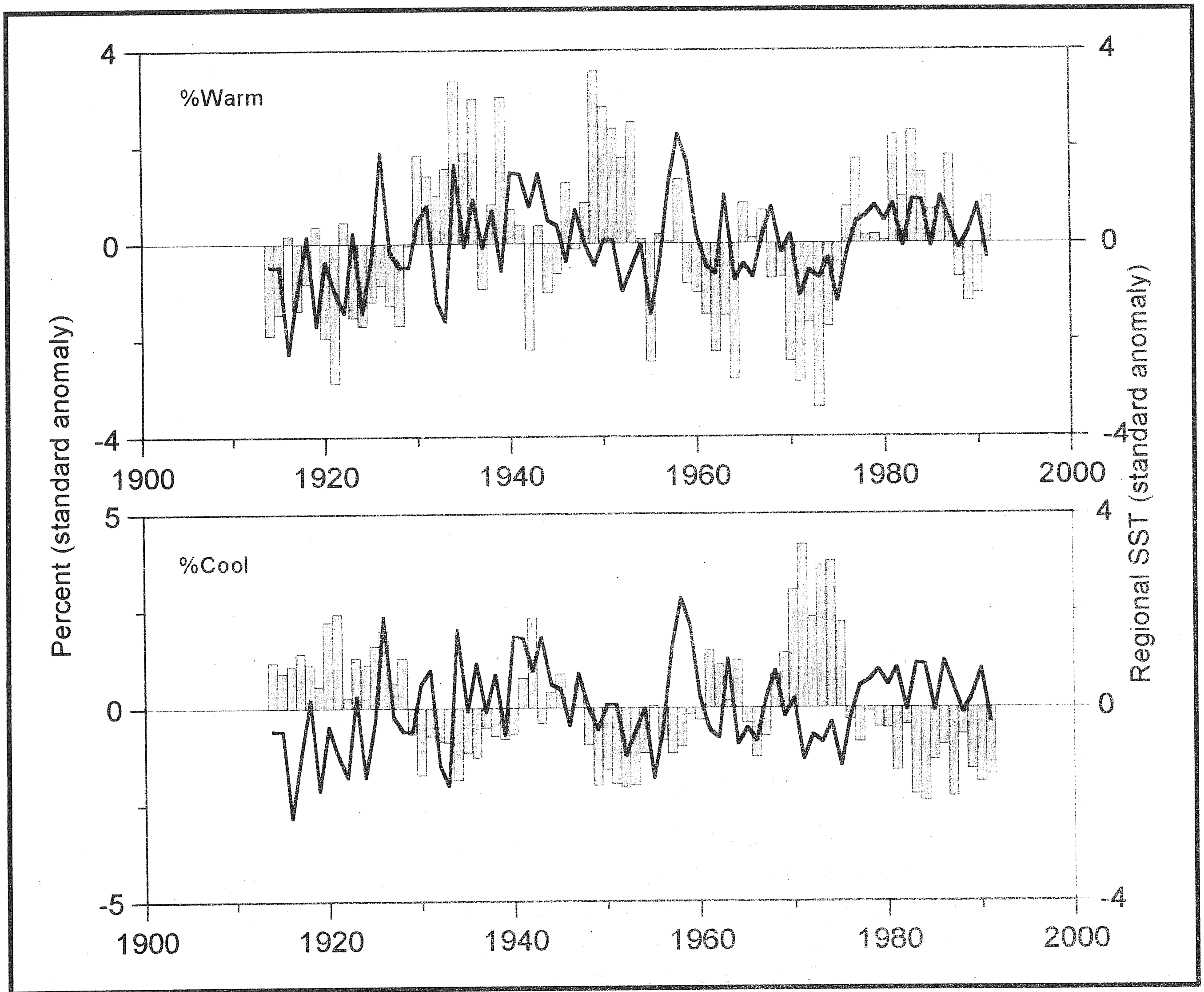

Figure 5 Upper panel: Relative accumulation rate of warm radiolarians (species with high fluxes in warm years or low fluxes in cool years) (bars) and the regional SST (solid line).
Lower panel: Relative accumulation rate of cool radiolarians (species with low fluxes in warm years or high fluxes in cool years) (bars) and the regional SST (solid line). All data are standard anomalies calculated over the period illustrated.

Neither fluxes of the SST or SLH classes (Figures 2, 3, 5, and 6) show a pattern related to the years of low Spearman rank correlation coefficients; therefore, it is unlikely that species entering during El Niños contribute much to the SST or SLH class fluxes, and perhaps they constitute a third discernible group within the radiolarian assemblage.

We hypothesize that the warm and high SLH classes of radiolarians would increase with SST and SLH, respectively. In general, fluxes follow this pattern, but during about 1930-1950, they are opposite to what we expect. The same is true for the cool and low SLH radiolarians, suggesting a problem with the chronology or a change in the relationship between the instrumental and the biological records. We doubt the chronology is off by more than plus or minus a few years, and it would have to be off by a decade or so to make the radiolarian and instrumental records fit.

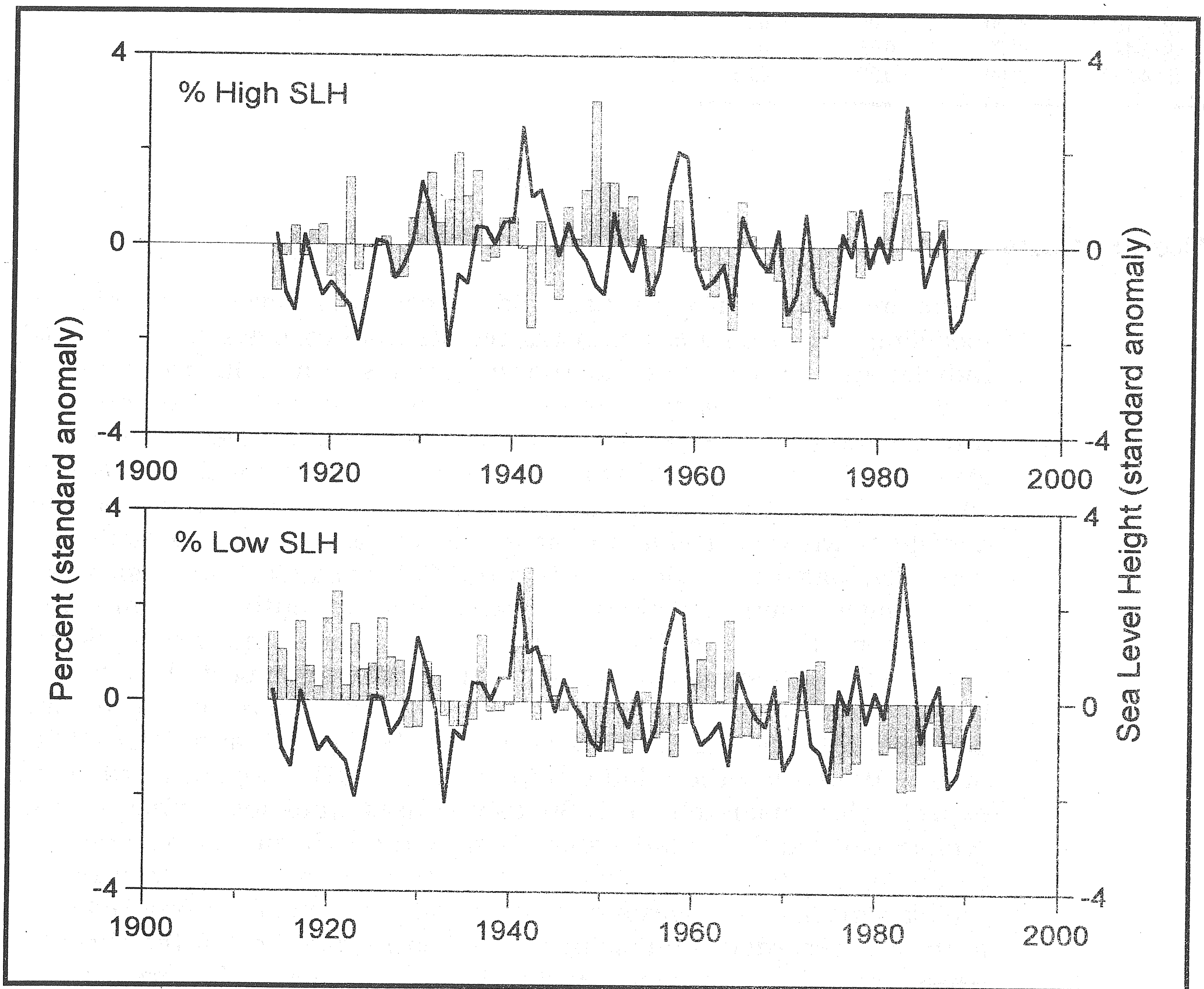

Figure 6 Upper panel: Relative accumulation rate of high SLH radiolarians (species with high fluxes in high SLH years or low fluxes in low SLH years) (bars) and annual SLH (solid line).
Lower panel: Relative accumulation rate of low SLH radiolarians (species with low fluxes in high SLH years or high fluxes in low SLH years) (bars) and annual SLH (solid line). All data are standard anomalies calculated over the period illustrated.

Table 1
CORRELATION COEFFICIENTS FOR
PERCENT SST AND SLH RADIOLARIAN GROUPS ON
SST AND SLH FOR THE YEARS USED TO DEVELOP
THE GROUPS (1955-1991),
THE VALIDATION PERIOD (1914-1954), AND
THE ENTIRE TIME SERIES (1914-1991)

Years	% Warm on % Cool	% Warm on SST	% Cool on SST
1914-1954	-0.89	0.03	-0.03
1955-1991	-0.77	0.53	-0.61
1914-1991	-0.80	0.14	-0.29

Years	% High on % Low	% High on SLH	% Low on SLH
1914-1954	-0.50	-0.08	0.02
1955-1991	-0.76	0.58	-0.53
1914-1991	-0.69	0.23	-0.23

Alternatively, the hydrography during 1930-1950 may have been anomalous, and the typical interpretation of SST and SLH as indicators of flow in the California Current System is inadequate.

Conclusions

Sediment from Santa Barbara Basin contains several records for modeling (paleo)climate. Promising results from analysis of the annual radiolarian record indicate that they may represent a multivariate history of climate. We have some optimism that total radiolarian accumulation rate generally reflects regional SST of decadal time scales, providing a general history of the California Current System. It is not clear, however, whether SST is truly the environmental variable controlling radiolarian density or whether it is just a surrogate for some other mechanism(s). Typically, warm SSTs prevail when the California Current is sluggish, upwelling is diminished and more water from the south and west enters the system. Since radiolarian density off California increases offshore and southward, similar to the pattern of SST, we expect their flux to increase with SST. Although the fluxes of total, percent warm, and percent cool reflect SST fairly well from 1950-1991 and 1914-1930, during 1930-1950 the relationship of flux to SST is opposite what we expect. The mismatch in 1930-1950 raises questions whether the radiolarian and SST relationship changes through time or whether the chronology of the core is inaccurate. The internal consistency of the radiolarian classes suggests that either some external force (not reflected in the SST record) is influencing the radiolarian flux or that the chronology is wrong, but this would require shifting the dates ±10 years to make the fluxes fit the instrumental record. We doubt this is entirely the case, based on correlations between this core (SBBC 9110 1302-2) and several others from Santa Barbara Basin. Distinct layers in the cores make correlations fairly straight forward, and multiple cores provide us many expressions of the varves from which to interpret the age.

If we accept that the chronology is accurate within a few years, then the radiolarian distributions in 1930-1950 with respect to the instrumental records is opposite to what our hypothesis predicts. Assuming the instrumental records reflect the oceanography of the California Current System, there should be evidence in the species structure indicating a definite shift in the assemblage. Measuring species structure with Spearman rank correlation coefficients does not reveal any changes until the late 1930s, several years after the mismatch begins, and the coefficients are only slightly lower than average. Although the species structure apparently did not change, groups of species can be identified that are inversely related through time, which shows that there was some variability in species structure. The Spearman rank correlation is not sensitive enough to detect these subtle changes in relative flux (rank) within a large assemblage of species with fairly constant ranks.

In future research, we will investigate the period of 1930-1950 to determine the character of the mismatch between the biological and instrumental records. By analyzing in greater detail the species composition for these two decades and correlating between the radiolarians and instrumental records at various lags, we should be able to better evaluate this period.

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