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Notes

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ABSTRACT

Warming of surface waters in the California Current since the 1950s has coincided with a significant decline in zooplankton volume. This has been attributed to reduced upwelling of nutrient-rich waters caused by increased thermal stratification across the thermocline. Proxy microfossil evidence preserved in the Santa Barbara Basin suggests that stability increased early in the 1900s, intensified after the early 1940s, and became well established by 1960. Accumulation of upwelled radiolarians in the basin has steadily declined since 1900, while oxygen isotopes in surface-dwelling planktonic foraminifera reflect increasing surface temperatures. Comparison of the δ^{18}O records between surface and thermocline-dwelling planktonic foraminifera reveals that the temperature difference between surface and thermocline water has increased during the twentieth century. Instrumental records of surface and thermocline temperatures, monitored since 1950, support these results. This evidence suggests that relaxation of North Pacific anticyclonic gyre circulation deepened isopycnics, causing onshore movement of warmer, less saline waters and reduced upwelling of cool, nutrient-rich waters.

INTRODUCTION

During the past several decades, productivity in the California Current system has declined significantly for macrozooplankton, fisheries, and marine bird populations (Roemmich and McGowan, 1995; Hayward, 1997; Smith, 1995; Veit et al., 1997). The anticyclonic North Pacific high and the cyclonic Gulf of Alaska–Aleutian low-pressure cells dominate atmospheric circulation over the North Pacific (Trenberth and Hurrell, 1994). During years marked by the high-pressure mode, southward advection and upwelling are strong along the eastern margin of the Pacific, forcing isopycnics upward, and bringing cool, high-salinity, nutrient-rich thermocline waters into the photic zone, thus increasing productivity (Reid et al., 1958; Chelton et al., 1982). Variability in production off California is more closely associated with this large-scale (Pacific basin) horizontal advection and oceanic upwelling than with coastal, wind-driven upwelling (Chelton et al., 1982).

The Santa Barbara Basin is at the northern end of the Southern California Bight. It is well located to sensitively record climatic change (Kennett et al., 1995; Weinheimer and Cayan, 1995; McGowan et al., 1998; Cannariato et al., 1999; Hendy and Kennett, 1999) and has annual layering (varves) (Soutar and Crill, 1977) ideal for high-resolution paleoclimatic investigations. McGowan et al. (1998) demonstrated that shore stations along the western United States, including Santa Barbara, represent regional coastal and North Pacific sea-surface temperatures (SSTs). Furthermore, cross-correlations between monthly SSTs at La Jolla, California, and global air and SSTs and sea-level pressure show that La Jolla SST reflects global climate variability (McGowan et al., 1998). There is strong evidence that the Santa Barbara Basin sedimentary record also reflects Pacific-wide fluctuations in oceanic and atmospheric conditions (Pisias, 1979; Dunbar, 1983; Lange et al., 1990; Schimmelmann et al., 1992; Weinheimer, 1994; Kennett and Ingram, 1995; Behl and Kennett, 1996; Weinheimer and Cayan, 1997; Herbert et al., 1998; Hendy and Kennett, 1999).

Oxygen isotopic studies of planktonic foraminifera collected in sediment traps in the Santa Barbara Basin indicate that *Globigerina bulloides* occupies waters of the surface mixed layer throughout the year (Pak et al., 1997). These records show that *Neogloboquadrina pachyderma* calcifies at a depth of ~60 m in the summer and fall warm period and migrates to shallower depths during spring upwelling. At this time, temperature changes associated with this upwelling caused a reduction in the δ^{18}O difference between *G. bulloides* and *N. pachyderma* (Pak et al., 1997). These results suggest that in this area, *G. bulloides* accurately reflects SST throughout the year and that the δ^{18}O difference between thermocline-dwelling *N. pachyderma* and surface-dwelling *G. bulloides* appears to be a reliable proxy for the depth of the thermocline (Pak et al., 1997) and hence the strength of surface stratification.

Radiolarians live at all water depths, and their biogeography is controlled mainly by water-mass distribution (Molina-Cruz, 1977; Weinheimer, 1994; Kling and Boltovskoy, 1995; Nigrini and Moore, 1979, and references therein), making them valuable tracers of subsurface water masses and circulation (Weinheimer and Cayan, 1997). Radiolarian species restricted to intermediate waters (below the main thermocline) off the southern California coast include *Lithomelissa setosa*, *Spongopyle osculosa*, and *Spongotrochus glacialis* and are the main species used to indicate the presence of subthermocline waters. Sediment trap samples from the Santa Barbara Basin show that high percentages of deep-dwelling radiolarians reflect upwelling of intermediate waters (Lange et al., 1997).

Sediment samples for this study were collected within the dysoxic zone of the Santa Barbara Basin (lat 34°13′N, long 120°03′W) using Soutar-style boxcores. Bacterial mats preserved the sediment surface during coring. Slabs of sediment from two box cores were X-ray radiographed and the varve ages determined by correlation to cores dated with ^{210}Pb (Soutar and Crill, 1977), water content (Schimmelmann et al., 1992), and varve counting from core tops downward. We estimate our margin of error at ±1 yr. Radiolarian data presented here are relative abundances per year determined from quantitative light-microscope slides of the >45 μm fraction. Samples were prepared following Wigley (1984). Planktonic foraminiferal species were picked from the >150 μm fraction for stable isotopic analysis; 20 shells of each species were analyzed. Tests were cleaned ultrasonically in deionized water, dried, and roasted under vacuum at 375 °C for 1 hr to remove organic contaminants. The samples were reacted in orthophosphoric acid at 90 °C with an on-line automated carbonate CO_2 preparation device, and the evolved CO_2 was analyzed at the University of California, Santa Barbara, by means of a Finnigan-MAT 251 light stable isotope mass spectrometer. Instrumental precision is 0.09‰ or better for δ^{18}O. All isotopic data are expressed in standard delta notation relative to the Peedee belemnite (PDB) carbonate standard. Replicate values in all cases were <0.181‰, with the exception of the 1982–1983 sample, which spanned as much as 0.314‰. The δ^{18}O records were converted to paleotemperatures using the equation of Erez and Luz (1983). The δ^{18}O of water was determined using the regression of Zahn et al. (1991).

INSTRUMENTAL HYDROGRAPHIC RECORDS

Surface and deeper records taken within the basin since 1953 are available (California Cooperative Oceanic Fisheries Investigations [CalCOFI] station 82.47). This station was occupied sporadically between 1953 and 1985 and monitored quarterly after 1985. It was occupied 136 times between 1953 and 1997. Correlation coefficients between CalCOFI station 82.47 and regional (lat 31–35°N, long 117–127°W) seasonal temperatures and salinities are highly significant; correlations range from ~0.5 to 0.8 (significant at >99%). Monthly averages were removed to avoid the strong seasonal signal and focus on the nonseasonal correlation.

Because the North Pacific atmospheric pressure system is a major driving force for the California Current system, we characterized the link between North Pacific sea-level pressure and southern California temperature and salinity for years of highest and lowest central North Pacific sea-level pressure (Fig. 1). During the 10 yr with lowest sea-level pressure between 1950 and 1996, monthly average temperatures were generally higher and salinities lower in waters off southern California than for the 10 yr of highest central North Pacific sea-level pressure (upwelling favorable) ($t = -1.46$, significant at 92%).

A composite of instrumental records from three sources is used to generate a spatially and temporally continuous time series of temperature and salinity for the Santa Barbara Basin region. The longest temperature and salinity records within southern California are surface measurements dating from 1916 at La Jolla. Records from Port Hueneme, which is closer to the basin, date from 1919, but salinity records were taken only through 1963; records at Santa Barbara began in 1955. We used the La Jolla records because of their long duration and because shore stations reflect regional conditions (McGowan et al., 1998).

For a record of water-column conditions, we included all available temperature and salinity data for the area 31°–35°N, 117°–127°W from the World Ocean Atlas and CalCOFI databases. This resulted in hundreds of observations from 1950 to 1995, i.e., several observations per year. Temperature and salinity at 0, 100, 200, and 400 m for the Southern California Bight and adjacent oceanic region were averaged over 1° squares. Monthly and annual averages were taken to generate the instrumental data presented here. Temperature and salinity time series on the $\sigma_{25.4}$ and $\sigma_{26.4}$ density levels were derived from these data. Pressure was calculated from depth assuming a 0 m reference pressure; potential temperature was calculated for standard depths; densities were calculated using the international equation of state. Depth, temperature, and salinity of the density levels $\sigma_{25.4}$ and $\sigma_{26.4}$ were linearly interpolated from standard depths.

Within the context of predominant multidecadal variability documented in longer marine sedimentary records (Baumgartner et al., 1992; Weinheimer and Cayan, 1997), instrumental records are too short to assess whether historical trends are unique or simply part of longer term climate fluctuations. However, for the limited period of the past four decades, we can emphasize recent climate trends by constructing temperature and salinity profiles for an early (1950–1964) and late (1979–1994) period (Fig. 2A). These two profiles for the Southern California Bight indicate that given temperatures and salinities within the permanent thermocline (50–200 m) were deeper in 1979–1994 than in 1950–1964. This is reflected in the density profiles for the two periods by a 10–20 m deepening of isopycnics in the later period (Fig. 2B). Hydrographic data for the entire past 40–50 yr interval indicates that temperatures have increased in the mixed layer and thermocline, while salinities have decreased (Fig. 2, C and D). Since the mid-1970s, North Pacific sea-level pressure has exhibited a deepening trend (Trenberth and Hurrell, 1994) and coincides with higher temperatures and lower salinities off the southern California coast. The changes through time of these multiple records indicate a tendency toward warmer, fresher, more stratified conditions.

PROXY RECORDS

Proxy records developed from varved Santa Barbara Basin sediments potentially can extend the relatively short instrumental records sufficiently for detecting decadal-scale climate change. In the Santa Barbara Basin, *Globigerina bulloides* lives in the upper 20 m of the water column (Pak et al., 1997). Comparison of paleotemperature and regional instrumental temperature at 0 m (Fig. 3A) indicates that this isotope record can be used as a proxy for SST change.

The paleotemperature record based on the $\delta^{18}O$ of *Neogloboquadrina pachyderma* exhibits cooling since 1960 (Fig. 3B), which was unexpected considering the warming evident in the instrumental records for a given depth (Fig. 2). Increased $\delta^{18}O$ values can also result from increased salinity. However, the salinity record reflects freshening since 1960 within the depth range of *N. pachyderma* (Fig. 2B). The apparent inconsistency between the *N. pachyderma* $\delta^{18}O$ and the instrumental records from a given depth led to an alternative interpretation of the isotope record. If we consider that the vertical distribution of planktonic foraminifera is determined in part by water densities, we can assume that *N. pachyderma* reflects the conditions at a particular density level. Results from sediment trap studies in the Santa Barbara Basin indicate that *N. pachyderma* lives within the thermocline at ~60–70 m depth (Pak et al., 1997). The temperature on the density level near this depth, $\sigma_{25.4}$, is generally reflected by the paleotemperature developed from the $\delta^{18}O$ of *N. pachyderma* (Fig. 3B). However, the *N. pachyderma* paleotemperatures for the early 1950s diverge from the instrumental

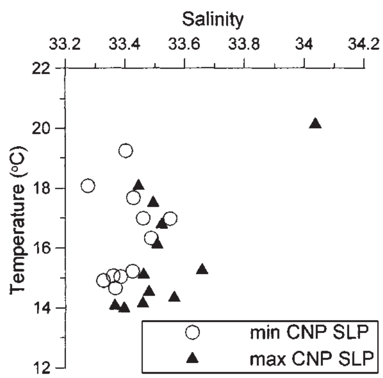

Figure 1. Average monthly temperature and salinity for La Jolla, California, for 10 yr of lowest (circle) and highest (triangle) winter central North Pacific sea-level pressure (CNP SLP) during period 1950–1994. Atmospheric data for area 35°–55°N, 170°E–150°W are used.

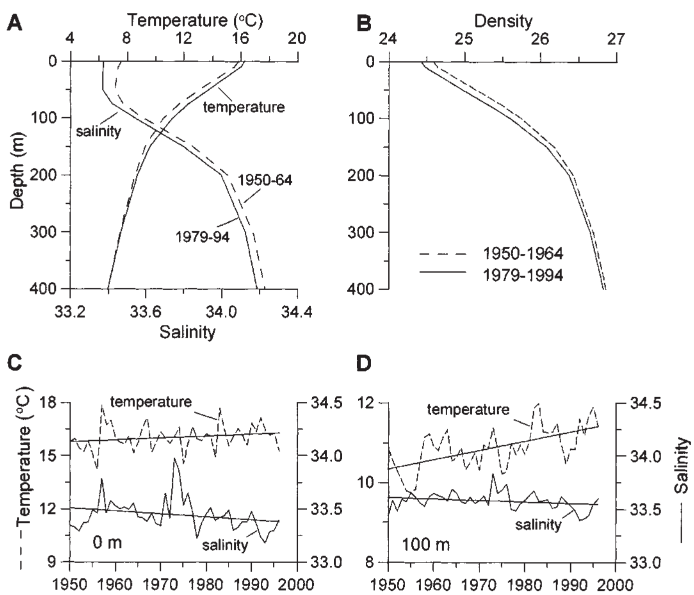

Figure 2. Average temperature and salinity (A) and density (B) of region off southern California (31°–35°N, 117°–127°W) at 0–400 m for 1950–1964 (dashed line) and 1979–1994 (solid line). C: 0 m annual average temperature (dashed line, linear regression yields 0.01 °C/yr change, Kendall's tau *p* = 0.097) and salinity (solid line, linear regression yields –0.003 ppm/yr change, Kendall's tau *p* = 0.049). D: 100 m annual average temperature (dashed line, linear regression yields 0.02 °C/yr change, Kendall's tau *p* = 0.000) and salinity (solid line, linear regression yields –0.001 ppm/yr change, Kendall's tau *p* = 0.106). Data in C and D are for 1950–1994 and the same region as A and B.

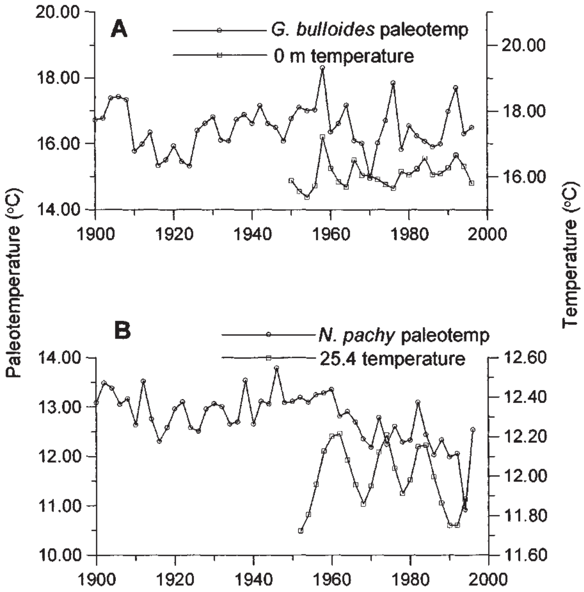

Figure 3. Time series of (A) *G. bulloides* paleotemperature (circle) with 3 yr running average of 0 m annual temperature for southern California region (square) and (B) *N. pachyderma* paleotemperature (circle) with 3 yr running average of annual temperature on 25.4 density level (square).

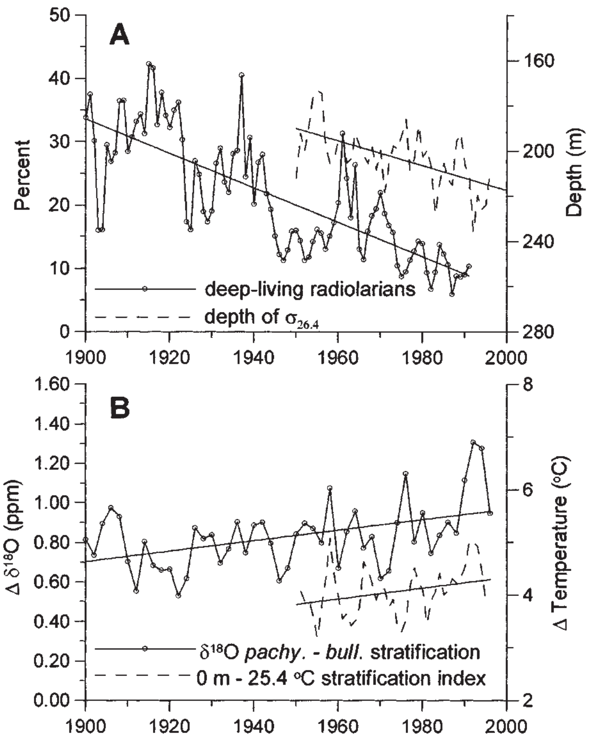

Figure 4. A: Percentage abundance deep-living radiolarians (circle, linear regression yields –0.27%/yr change, Kendall's tau $p = 0.00$) and annual average depth for 26.4 density level off southern California (dashed line, linear regression yields –0.10 m/yr change, Kendall's tau $p = 0.00$). B: Index of stratification based on instrumental annual average temperature difference between 0 m and 25.4 density level, 1950–1994 (dashed line, 3 yr running average; linear regression yields 0.01 °C/yr change, Kendall's tau $p = 0.189$), and based on difference between $\delta^{18}O$ *N. pachyderma* and *G. bulloides*, 1900–1995 (2 yr interval; circle, linear regression yields 0.003 ppm/yr change, Kendall's tau $p = 0.006$).

temperature record. This comparison of proxy and instrumental records indicates that paleotemperature reconstructions from $\delta^{18}O$ of *N. pachyderma* closely estimate thermocline water temperatures, for most of the time, but anomalies indicate that caution is needed for detailed applications. Note that salinity probably does not significantly affect the isotopic record. On average, a salinity increase of 1 ppm results in a 0.5 ppm increase in $\delta^{18}O$ (Craig and Gordon, 1965; Berger and Gardner, 1975). The $\delta^{18}O$ time series of *G. bulloides* and *N. pachyderma* are nearly parallel, but diverge, especially after 1960.

The percent of deep-living radiolarians (species restricted to intermediate waters of 5–10 °C and >34.0 salinity) reflects the depth of the thermocline (Lange et al., 1997). In the Southern California Bight, basal thermocline water has a density of ~26.4 (Fig. 2B). After 1950, the percent of deep-dwelling radiolarians declined as the $\sigma_{26.4}$ deepened (Fig. 4A). Radiolarian assemblages reflect the trend in the depth of the $\sigma_{26.4}$ level, although not all details are exhibited in the instrumental record. A strong decline in the percentage of deep-living radiolarians occurred over the past century, with a steplike drop in the early 1940s.

STRATIFICATION OVER THE PAST CENTURY

We generated a longer record of upper water column behavior using microfossil and oxygen isotopic data obtained for most of the twentieth century from the Santa Barbara Basin sediments. Key habitats in studying water-column stability are the waters above, within, and below the thermocline. We used the oxygen isotopic composition of *Globigerina bulloides* and *Neogloboquadrina pachyderma* and the percent abundance of deep-living radiolarians to represent these parts of the water column, respectively. The decline in percentage of deep-living radiolarians suggests that isopycnics at the base of the thermocline have been deepening since the turn of the century.

We constructed a historic record of stratification in surface waters for the oceanic region off southern California by determining the difference in instrumental temperature at 0 m and $\sigma = 25.4$ for the past ~50 yr (Fig. 4B). This record indicates that stratification has steadily increased since the beginning of the record in 1950. We also constructed a proxy record of stratification for the past 100 yr, using the $\delta^{18}O$ difference between *N. pachyderma* and *G. bulloides* (Fig. 4B). The upward-trending proxy record parallels that of the instrumental stratification record since 1950. Although there are small differences in detail between the two records, planktonic foraminiferal oxygen isotopes appear to provide a reliable record of changing water-column stability and SST. Discrepancies may be due to the large region represented by the instrumental record compared to the smaller part of this region represented by the foraminifera. Furthermore, the results suggest that surface water stability has increased during the past 100 yr.

CONCLUSIONS

Multiple microfossil proxies from the Santa Barbara Basin and instrumental records indicate trends of warming and increasing stratification during the twentieth century. A cooling signal in the *N. pachyderma* $\delta^{18}O$ record coincides with an interval of warming evident in instrumental temperature records for any given depth (Fig. 2). This apparent discrepancy is explained by comparing the *N. pachyderma* $\delta^{18}O$ record to temperatures on a density level, in contrast to a specific depth. Similarities between the isotopic proxy for stratification and instrumental index show that this proxy is a reliable indication of stratification across the thermocline. Since 1900, two abrupt changes occurred at depth, but have no apparent expression in the mixed layer. Deepening of isopycnal surfaces in the 1940s is signaled by the sudden decline in percentage abundance of deep-living radiolarians and in 1960 by rapid cooling in the *N. pachyderma* $\delta^{18}O$ record. These changes in the vertical structure of the water column are superimposed on a gradual surface-water warming since 1900.

Increased stratification of the water column and stability in the thermocline during the twentieth century are associated with deepening isopycnics. Apparently, the change toward a more stable vertical structure of the water column was not restricted to the region off southern California; the thermocline depth around the Galapagos Islands deepened in the mid-1970s and coincided with diminished zonal winds (Guilderson and Schrag, 1998). As stratification has increased and isopycnics deepened, the water column has freshened and warmed, conditions characteristic of low central North Pacific sea-level pressure periods. Deepening of isopycnics may have been in response to relaxation of the North Pacific Ocean anticyclonic circulation, consistent with a strengthening of the Aleutian low system. A combination of deeper nutrient-rich waters and increased thermal stratification has reduced biological production.

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