6-2004

Enhanced Marine Productivity Off Western North America During Warm Climate Intervals of the Past 52 k.y.

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ABSTRACT

Studies of the Santa Barbara Basin off the coast of California have linked changes in its bottom-water oxygen content to millennial-scale climate changes as recorded by the oxygen isotope composition of Greenland ice. Through the use of detailed records from a sediment core collected off the Magdalena Margin of Baja California, Mexico, we demonstrate that this teleconnection predominantly arose from changes in marine productivity, rather than changes in ventilation of the North Pacific, as was originally proposed. One possible interpretation is that the modern balance of El Niño–La Niña conditions that favors a shallow nutricline and high productivity today and during warm climate intervals of the past 52 k.y. was altered toward more frequent, deep nutricline, low productivity, El Niño–like conditions during cool climate intervals.

Keywords: millennial-scale climate, abrupt climate change, foraminifera, marine productivity, paleo-ENSO variability.

INTRODUCTION

Phytoplankton in marine eastern boundary currents like the California Current (Fig. 1A) flourish owing to elevated nutrient concentrations resulting from wind-driven coastal upwelling (Huyer, 1983; Thomas et al., 2001). These regions exhibit significantly reduced primary productivity during El Niño years when alongshore winds are not only weaker (Mantua et al., 2002) but, more significantly, the nutrient concentrations in the upwelled source water are lowered by a deepening of the thermocline (Chavez et al., 2002).

On longer time scales, the sensitivity of the region to climate change has been established by spectacular records from the Santa Barbara Basin off the coast of central California, where sediment accumulates at a rate of ~170 cm/k.y. and modern conditions are nearly anoxic (Kennett and Ingram, 1995). Under such conditions, millimeter-scale laminations reflecting seasonal variations in sediment composition are preserved because burrowing benthic fauna that stir the sediment cannot survive (Soutar and Crill, 1977). Behl and Kennett (1996) argued that, in contrast, oxic conditions led to bioturbation during climate intervals cooler than today such as the Younger Dryas, marine isotope stage 2, and the stadial events of marine isotope stage 3, which extended from ca. 60 ka to 29 ka. A key feature of the Santa Barbara Basin record is the occurrence of 17 zones of preserved laminations during marine isotope stage 3, each ~1 k.y. in duration. The timing of these laminations corresponds to the warm interstadial events identified by using various climate proxies extracted from Greenland ice (Grootes et al., 1993). Because the source waters on the open margin that supply the basin reside within the North Pacific oxygen-minimum zone (Fig. 1B), the prevailing interpretation of the interstadial events recorded by the laminations in the basin has been that they arose from decreases in North Pacific ventilation (Behl and Kennett, 1996; Cannariato and Kennett, 1999). Here we challenge this interpretation through the use of a series of detailed proxy records from a site on the Magdalena Margin off Baja California, ~1500 km south of the Santa Barbara Basin.

RESULTS

In November 1999, a 15 m composite section of alternating laminated and bioturbated sediment consisting of gravity core MV99-GC31 and piston core MV99-PC08 was raised onboard the RV *Melville* from a depth of 700 m (van Geen et al., 2001). The Magdalena Margin site is located within the oxygen-minimum zone under bottom-water oxygen concentrations of 2 μmol/kg. A total of 16 accelerator mass

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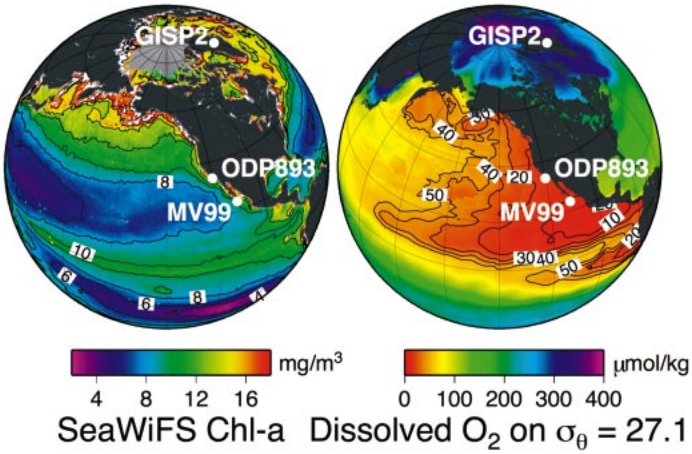

Figure 1. Controls on sedimentary organic carbon off Baja California. Left: Annually averaged phytoplankton pigment (mg/m^3) in North Pacific based on satellite-derived Chl-a data from 1998 to 2002 provided by SeaWiFS Project, National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and ORBIMAGE. Right: Annually averaged dissolved oxygen (μmol/kg) on 27.1σ_θ density surface (which corresponds to depth of Baja California study site) based on data from Levitus and Boyer (1994). Locations of cores from Baja site (MV99), Santa Barbara Basin (Ocean Drilling Program [ODP] Site 893), and Greenland Ice Sheet Project 2 (GISP2) are labeled in white. Data are plotted with Generic Mapping Tools software (Wessel and Smith, 1998).

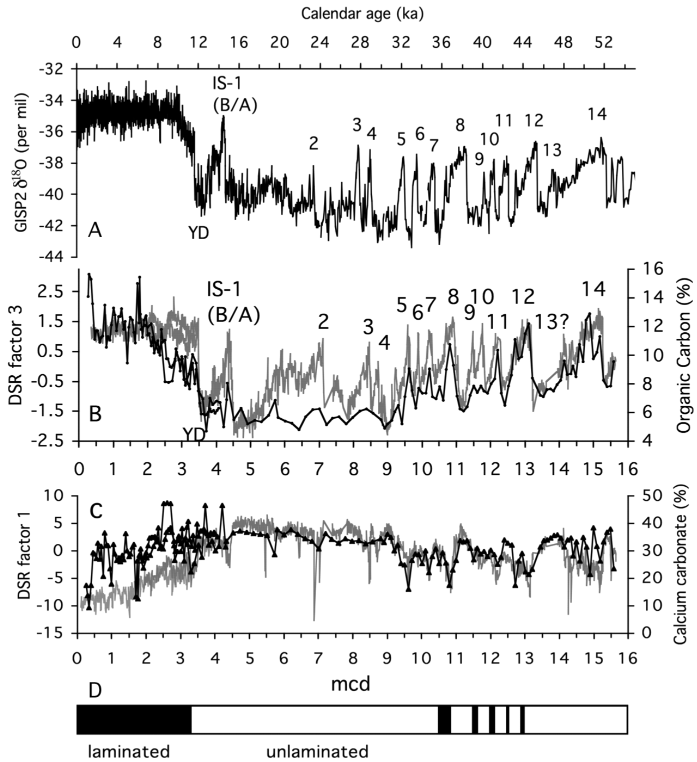

Figure 3. Climate records for past 52 k.y. A: Greenland Ice Sheet Project 2 (GISP2) δ^{18}O values from Grootes et al. (1993) plotted as function of calendar age. Labels indicate interstadial (IS) events 1–14 as identified by Grootes et al. (1993). B: Diffuse spectral reflectance (DSR) factor 3 at 1 cm resolution from cores GC31 (gray line) and PC08 (black line) off Baja California, plotted against meters composite depth (mcd). Labels indicate interstadial events 1–14. Estimates of organic carbon (circles) by difference of total carbon and total inorganic carbon using data generated by U.S. Geological Survey (USGS) are shown for comparison. C: DSR factor 1 at 1 cm resolution from cores GC31 (gray line) and PC08 (black line). Calcium carbonate data (triangles) generated by USGS are shown for comparison. D: Lithology for Baja California composite section. Laminated intervals are indicated by shaded bars. YD—Younger Dryas; B/A—Bølling-Ållerød.

spectrometry (AMS) ^{14}C dates measured on the tests of benthic foraminifera indicates, after conversion to calendar years (van Geen et al., 2003), a remarkably constant sedimentation rate of ~30 cm/k.y. over the past 35 k.y. (Fig. 2). Sedimentation rates are constant here despite changes in sedimentary organic carbon (Fig. 3B) and carbonate content (Fig. 3C) due to a compensating decrease in sedimentary dry bulk density in intervals with high organic carbon (C_{org}) content. Comparison of the onset of Holocene laminations in the two cores of the composite section and comparison with the most recent pattern of laminations recorded by a multicore from the same location indicate a loss of 0.25 m from the top of the gravity core and 1.81 m from the top of the piston core relative to the top of the multicore because of coring (Fig. 3B).

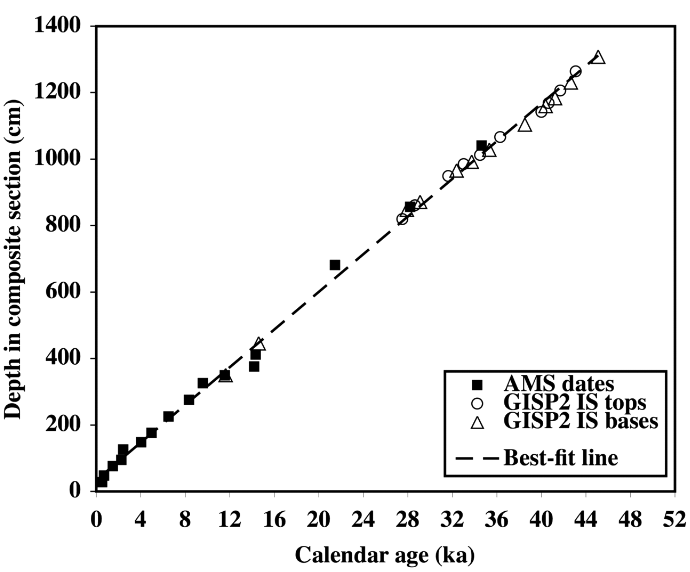

Figure 2. Age model, based on three types of data, for Baja California composite section. Solid squares—calendar year–corrected accelerator mass spectrometer (AMS) ^{14}C dates from van Geen et al. (2003). Open circles—stratigraphic picks corresponding to tops of warm interstadial (IS) events identified in diffuse spectral reflectance (DSR)-3 record by using Greenland Ice Sheet Project 2 (GISP2) age model of Grootes et al. (1993). Open triangles—stratigraphic picks corresponding to bottoms of warm interstadial events identified in DSR-3 record by using GISP2 age model of Grootes et al. (1993).

The age model for the Baja California cores was extended further back in time by using shipboard diffuse spectral reflectance (DSR) measured at 1 cm resolution on freshly split cores with a Minolta CM-2022 spectrophotometer (Figs. 2 and 3). Previous work has shown that DSR color spectra can be related to bulk sediment composition in many environments (Balsam and Deaton, 1991; Mix et al., 1999; Ortiz et al., 1999). For the Baja California record, a three-component R-mode factor model of the first-derivative transform of the percent reflectance spectra accounts for >93% of the data variance. DSR factor 3, which accounts for 10% of the variance, bears a striking resemblance to the δ^{18}O record preserved in the Greenland Ice Sheet Project 2 (GISP2) ice core (Grootes et al., 1993) and to the C_{org} content of the core (Figs. 3A, 3B). DSR factor 1, which accounts for 60% of the variance, relates to the calcium carbonate content of the core (Fig. 3C). Minima in the DSR factor 1 record correspond to low carbonate values during interstadial events. An extended age model, based on the assumption that the peaks and troughs in DSR factor 3 loadings correspond to warm interstadial and cool stadial events 1–14 in the GISP2 ice core (Grootes et al., 1993), is entirely consistent with the radiocarbon data and indicates that the sedimentation rate at this site has not varied appreciably for the past 52 k.y. (Fig. 2). This Baja California site is therefore particularly well suited for studies of climate change.

DISCUSSION AND CONCLUSIONS

Comparison of the reflectance record and C_{org} measurements from the same core indicates that there is a positive correlation between the DSR factor 3 loadings and the amount of plankton material that has escaped mineralization in the water column or the sediment (Fig. 3B). During the 52–30 ka interval in particular, peaks in DSR factor 3 correspond closely in magnitude and shape to variations in both C_{org} in the same core and variations in $\delta^{18}O$ in Greenland ice (Figs. 3A, 3B). Carbonate content in the core is inversely correlated with C_{org} content (Fig. 3C), reaching maximum values during cool glacial and stadial climate intervals, as is typically seen in the California Current (e.g., Gardner et al., 1997). This suggests greater carbonate dissolution during organic-rich interstadial events.

But does the increase in C_{org} concentration reflect an increase in export production or an enhancement of sedimentary C_{org} preservation? To evaluate whether the northeast Pacific pattern of increased C_{org} content and intermittent laminations during warm interstadial climate intervals was primarily driven by changes in productivity or ventilation, two additional proxies based on the carbonate fraction were measured in the Baja California cores. At a depth resolution of as much as 5 cm (equal to an ~170 yr interval), a calibrated volume of sediment was washed and sieved to determine the concentration of benthic foraminifera (primarily *Bolivina* and *Uvigerina* species) and carbonate fragments from broken tests of foraminifera (primarily planktonic *Globigerina* and *Neogloboquadrina* species) per gram of sediment. Previous work has documented the relationship between the flux of organic matter to the seafloor and the concentration of benthic foraminifera per gram of sediment (Herguera and Berger, 1994). At the Baja California site there is a striking correspondence between this measure of export production and DSR factor 3: maxima in factor loadings and C_{org} correspond to an almost 100-fold-higher benthic foraminiferal concentration compared to intervening stadial periods (Figs. 4A, 4B). This finding suggests that the productivity of surface waters at this location along the northeast Pacific margin (Fig. 1) was drastically lower during past cool stadials and the Last Glacial Maximum than it was during the Holocene and past warm episodes.

Could the benthic foraminiferal concentration variations be a preservational artifact? Corrosive dissolution of calcium carbonate can result from the elevated supply of organic matter (Emerson and Bender, 1981). However, such a mechanism cannot explain our data because the benthic foraminiferal concentration was actually higher during periods of elevated C_{org} accumulation, despite poor overall carbonate preservation (Fig. 4C). Alternatively, pore-water conditions that became reducing enough to reach the sulfate reduction stage could have enhanced carbonate preservation (Berger, 1970; Reimers et al., 1996; Kuwabara et al., 1999). The foraminiferal fragmentation record, a standard indicator of carbonate dissolution (Berger, 1975), provides some evidence against this explanation. The concentration of fragments per gram, which varies by 10-fold, exhibits a weak positive correlation with the benthic foraminiferal concentration per gram (Figs. 4B, 4C; $r = +0.51$; $p > 0.1$; $n = 33$), a relation opposite to the one expected if the preservation of benthic foraminifera had been controlled primarily by sulfate reduction. These arguments suggest that variations in the DSR factor 3 record, C_{org} concentration, and benthic foraminiferal concentration per gram were driven primarily by large shifts in the organic productivity of the overlying waters.

What implications might these large shifts in organic production have for the interpretation of the Santa Barbara Basin lamination record? Intensification of the northeast Pacific oxygen-minimum zone due to a decrease in North Pacific intermediate-water ventilation has generally been invoked to explain the laminations in the basin. Today, however, the bottom-water oxygen content of the basin is significantly reduced relative to its source waters on the adjacent margin because of locally enhanced productivity (Reimers et al., 1996; van Geen et al., 2003). Stott et al. (2000) also challenged the traditional interpretation of the basin records by noting that the pattern of laminations in other silled basins of the California Borderlands during recent decades appears to have been driven by variations in productivity. While the C_{org} record from the Santa Barbara Basin lacks interstadial peaks, interstadial maxima in the concentration of the upwelling-related planktonic foraminifera *G. bulloides* provide evidence of increased production within the basin during warm periods (Hendy and Kennett, 2000). Likewise, high C_{org} accumulation during warm interstadial events is observed in cores throughout the Oregon and California margins (Gardner et al., 1997; Mix et al., 1999). Such evidence, combined with our open-margin results from the Baja California site, suggests that warm interstadial events, including present conditions, were associated with elevated productivity over much of the northeast Pacific. Although it may well be that ventilation of the northeast Pacific was also enhanced during cold periods and reduced during warm periods (Zheng

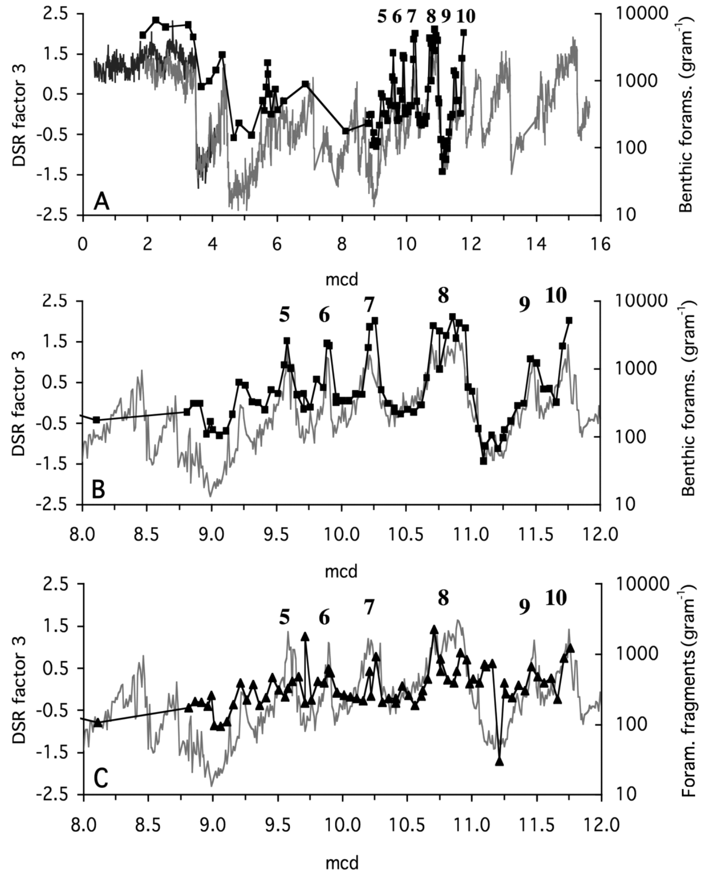

Figure 4. Relationship between marine production and carbonate dissolution off Baja California. A: Diffuse spectral reflectance (DSR) factor 3 loadings from cores GC31 (black line) and PC08 (gray line) and concentration of benthic foraminifera per gram of sediment (squares) plotted as function of meters composite depth (mcd) for entire core. Interstadial events 5–10 as identified by Grootes et al. (1993) are labeled for reference. B: Close-up of concentration of benthic foraminifera per gram of sediment during interstadial events 5–10. DSR factor 3 loadings (gray line) are plotted for reference. C: Accumulation of foraminiferal fragments per gram of sediment during interstadial events 5–10. DSR factor 3 loadings (gray line) are plotted for reference.

et al., 2000), it appears that this effect may have served only to modulate the effect of enhanced productivity on the intensity of the oxygen-minimum zone in the northeast Pacific over the past 52 k.y. Such modulation may explain occasional decoupling between the various proxies (Fig. 3). Laminations in sediments off Baja California, for example, were preserved only during the Holocene and the more pronounced interstadial events, when C_{org} fluxes were particularly high. In contrast, smaller interstadial events are represented by unlaminated sediments. Overprints possibly driven by changes in ventilation may also explain why the scaling between DSR factor 3 and C_{org} shifts during marine isotope stage 2.

The inferred teleconnection between global climate and regional productivity in the northeast Pacific may have significant implications for understanding the dynamics of the North Pacific ocean-atmosphere system on millennial time scales. Research on the response of the equatorial and North Pacific to the El Niño–Southern Oscillation climate cycle indicates that a deepening of the thermocline, and weakening of the nutricline, provides one means to significantly reduce the productivity in this region during El Niño years (Chavez et al., 2002). Published $\delta^{15}N$ records from other locations along the California margin (Emmer and Thunell, 2000; Kienast et al., 2002) suggest enhanced denitrification during warm interstadial events and thus a potential NO_3 deficit in interstadial surface waters relative to the stadial surface waters off Baja California. Higher productivity indicated by our proxies during such a nutrient regime thus implies the need for a greater nutrient flux to the surface waters during warm intervals to overcome this deficit. We thus suggest a shift of the mean state toward more El Niño–like conditions with a regionally deepened nutricline as an important factor distinguishing cool climate periods from warm periods such as the Holocene. Such a model is consistent with current theories (Clement et al., 1999) and proxy reconstructions of the equatorial Pacific (Koutavas et al., 2002; Stott et al., 2002).

ACKNOWLEDGMENTS

We thank Kent State University students N. Saraceno and M. Wilsbacher for their help in the laboratory. Lowell Stott, Wolf Berger, and an anonymous reviewer provided helpful reviews. This work was supported by National Science Foundation (NSF) grants OCE-98-09026, OCE-02-14221, and OCE-02-14646, and by the Kent State University Farris Fund for Excellence. The sediment cores used for this project are stored at Lamont-Doherty Earth Observatory (LDEO) Deep-Sea Sample Repository, supported through NSF grant OCE-00-02380 and Office of Naval Research grant N00014-02-1-0073. This is LDEO contribution 6576.

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Manuscript received 13 October 2003
Revised manuscript received 2 February 2004
Manuscript accepted 4 February 2004

Printed in USA