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Dansgaard-Oeschger cycles and the California Current System: Planktonic foraminiferal response to rapid climate change in Santa Barbara Basin, Ocean Drilling Program hole 893A

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Abstract. High-resolution planktonic foraminiferal census data from Santa Barbara Basin (Ocean Drilling Program hole 893A) demonstrate major assemblage switches between 25 and 60 ka that were associated with Dansgaard-Oeschger cycles. Stadials dominated by *Neogloboquadrina pachyderma* (sinistral), and *Globigerinoides glutinata* suggest a strong subpolar California Current influence, while interstadials marked by abundant *N. pachyderma* (dextral) and *G. bulloides* indicate a relative increase in subtropical countercurrent influence. Modern analog technique and transfer function (F-20RSC) temperature reconstructions support $\delta^{18}O$ evidence of large rapid (70 years or less) sea surface temperature shifts (3° to 5°C) between stadials and interstadials. Changes in the vertical temperature gradient and water column structure (thermocline depth) are recorded by planktonic faunal oscillations suggest bimodal stability in the organization of North Pacific surface ocean circulation. Santa Barbara Basin surface water demonstrates the rapid response of the California Current System to reorganization of North Pacific atmospheric circulation during rapid climate change.

1. Introduction

It has been well established that the last glacial episode was marked by significant climate instability. First identified in the Greenland Ice Sheet, the series of warm, brief interstadials (Dansgaard-Oeschger (DO) events), which punctuated the cool conditions of the last glacial [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993], now appear to be global climate events [*Hendy and Kennett*, 1999; *Wang et al.*, 1998]. Progress toward understanding the extent of surface ocean ecosystem and atmospheric/oceanic change associated with these large, decadal-scale climate oscillations in the geologic record requires high chronological resolution investigations. The 196.5 m long Ocean Drilling Program hole 893A from Santa Barbara Basin (34°17.25'N, 120°2.2'W; 576.5m water depth) is the highest-resolution record of late Quaternary (160 ka to present) climate change from the ocean. Thus the opportunity is provided to examine rapid climate change in the oceanic environment. The presence of intermittently laminated intervals [*Behl and Kennett*, 1996] at ODP hole 893A associated with anoxic events in the basin [*Cannariato et al.*, 1999; *Cannariato and Kennett*, 1999] has previously been demonstrated to closely correlate with the DO cycles recorded in the Greenland Ice Core (GISP2).

Oxygen isotope ($\delta^{18}O$) records for both surface and thermocline-dwelling foraminiferal species have been produced, clearly defining rapid climate variability in Santa Barbara Basin surface waters and suggesting significant temperature change was associated with DO events [*Hendy and Kennett*, 1999]. However, salinity and ice volume as well as water temperature influence $\delta^{18}O$ values. Ice volume changes were only a minor influence over the short time intervals associated with rapid switches in climate state (50 years or less [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993]). However, atmospheric reorganization over the North Pacific during DO events undoubtedly produced shifts in southern Californian precipitation [*Heusser*, 1998; *Cooperative Holocene Mapping Project Members*, 1988], which may have affected $\delta^{18}O$ values at ODP hole 893A owing to the close proximity (20 km) of the North American continent.

Here we present two independent methods of estimating paleotemperatures using census data to determine the relative magnitude of temperature shifts: Imbrie-Kipp transfer function (F-20RSC) and modern analog technique (MAT). Also, planktonic foraminiferal census data provide evidence of significant and rapid oscillations in the physical structure of the upper water column of Santa Barbara Basin associated with large sea surface temperature (SST) shifts. Changes in the upper water column increase the significance of broad regional changes in surface ocean circulation in the North Pacific (specifically the California Current System). We present evidence from census data confirming the presence of large temperature shifts and demonstrating that changes in the relative strength of the California Current System and possibly coastal upwelling caused significant changes in the surface ocean biosphere.

2. Oceanographic Setting of Santa Barbara Basin

The highly productive Santa Barbara Basin provides an ideal site for studying the effects of rapid climate change on the upper water column. An extremely high sedimentation rate of 140 cm kyr^{-1} is produced by high siliciclastic sedimentation during winter rain storms and high productivity through late spring summer upwelling [*Thunell*, 1998]. The sill depth (475 m) of the basin lies within the oxygen minimum zone, and bathyal waters (upper Pacific Intermediate Water) are further depleted of oxygen by organic matter degradation from surface productivity. Benthic

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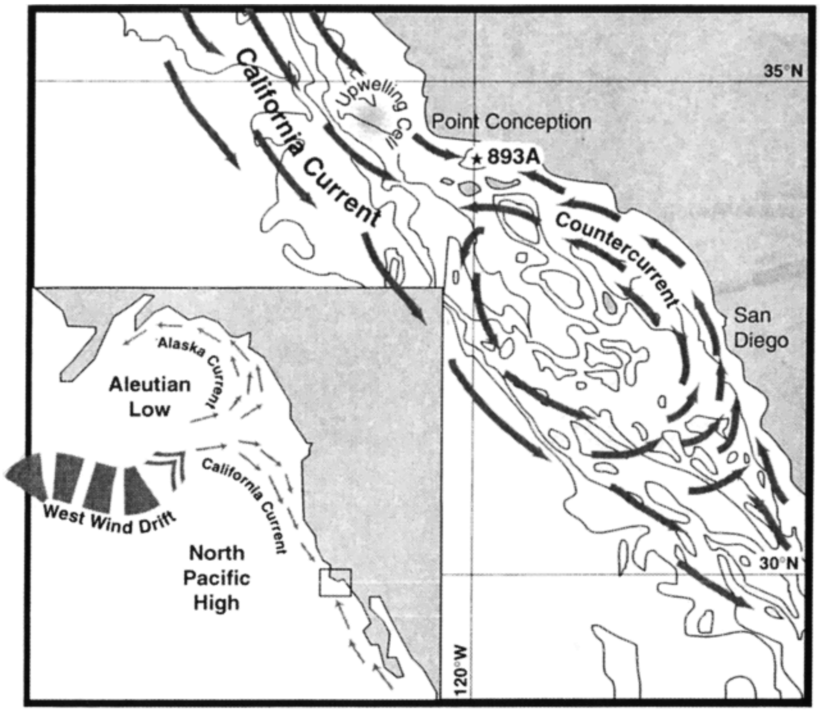

Figure 1. Map showing both the location of Ocean Drilling Program hole 893A, Santa Barbara Basin, and the relationship between surface ocean currents on the Southern California continental margin which influence Santa Barbara and broad atmospheric circulation over the north Pacific.

macrofauna is excluded by the low-oxygen conditions, so the resulting lack of bioturbation retains the switches in seasonal sedimentary sources as laminations with excellent, undisturbed preservation of organic material [*Behl*, 1995].

Regional surface circulation is dominated by the eastern boundary of the California Current, which flows south along the outer edge of the California borderland before to turning toward the coast at San Diego (Figure 1) [*Lynn and Simpson*, 1987; *Reid et. al.*, 1958]. Central borderland surface flow is dominated by the northerly flowing Southern California Countercurrent, forming a counterclockwise gyre (Borderland Gyre) in the Southern California Bight (Figure 1) [*Lynn and Simpson*, 1987]. Although the bulk of California Current flow is west of Santa Barbara Basin [*Lynn and Simpson*, 1987], changes in the relative strength of regional currents are recorded at ODP hole 893A. The relative contributions of cool, low-salinity, nutrient-rich California Current and warm California Countercurrent water in the basin [*Hendershott and Winant*, 1996] (Figure 1) are a product of surface flow intimately linked to ocean-atmosphere interactions over the North Pacific Ocean. The seasonal northward migration of the north Pacific high-pressure cell in spring and summer produce the predominant northerly winds associated with the California Current and upwelling [*Reid et al.*, 1958].

SSTs recorded at the center of Santa Barbara Basin reflect the annual shifts in current activity in the region. SST at 0 to 5 m depth range from 13° to 17°C [*Thunell*, 1998] throughout the year but are warmer during El Niño events. The warmest temperatures occur in fall (August to November) as the relative strength of the California Countercurrent and the Borderland Gyre in the southern California borderland is increased when predominant northerly winds diminish [*Hendershott and Winant*, 1996]. The coolest temperatures occur in spring to early summer (March to June) [*Thunell*, 1998], when northerly winds intensify the California Current and drive Ekman-induced upwelling off Point Conception [*Hendershott and Winant*, 1996]. As a result, climatic events affecting North Pacific atmosphere and ocean circulation amplify SST variations in the basin.

Oscillations in the upper water column recorded at ODP hole 893A have been attributed to restriction of advected flow over the shallow basin sills of Santa Barbara Basin (particularly at the southern end) during eustatic low sea level [*Gardner and Dartnell*, 1995]. However, active tectonics and high uplift rates of the region have counteracted restriction of flow during the lower sea levels of marine isotope stage (MIS) 3. Rapid regional coastal uplift (>5 mm yr^{-1} at the southern entrance) [*Huftile and Yeats*, 1995] over the last glacial produced similar if not wider entrances to Santa Barbara Basin than present. Thus the maximum 80 m lower global sea level during the MIS 3 would have negligible effects on currents entering the basin.

3. Methods

A high-resolution planktonic foraminiferal assemblage record for MIS 3 was generated from 577 samples from 30 to 80 m depth in ODP hole 893A.[1] Samples were taken at 7 cm intervals in 2

[1] Supporting assemblage data are available on diskette or via Anonymous FTP from Kosmos.agu.org, directory APEND (username = anonymous, Password = guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; $15.00. Payment must accompany order.

cm slices, creating 14 year-averaged samples at a temporal resolution of between 50 and 70 years. Samples were processed using standard techniques [*Kennett*, 1995]. Faunal counts were based on ~300 specimens in the >125μm sediment size fraction. However, when a sample contained <50 individuals, it was removed from the census database. The total abundance of specimens is presented in this contribution as the number of specimens of each species contained in 1 cm^3 of sample. Relative abundance is presented as the percentage contribution of each species to the census. Following standard procedure, both coiling variants of *Neogloboquadrina pachyderma* were counted individually. Thus the ratio of sinistral to dextral *N. pachyderma* specimens is presented as well as the total abundance of each morphology. Recent molecular biological studies suggest the two different coiling morphologies (sinistral and dextral) of *N. pachyderma* are separate species [*Darling et al.*, 1999].

A Q mode factor analysis with varimax rotation of the foraminiferal census data was undertaken using the computer program CABFAC [*Imbrie and Kipp*, 1971]. We have employed two factors in this study to display faunal assemblage shifts between stadials and interstadials. Methods employed in producing temperature estimates based on the planktonic foraminiferal faunal census are discussed in sections 4.1, 4.2, and 4.3.

The chronology of the last 60 kyr (calendar years) at ODP hole 893A follows *Behl and Kennett* [1996], based on a fit of 17 accelerator mass spectrometry radiocarbon dates (Table 1) [*Ingram and Kennett*, 1995] between 28,896 Ka and present (r^2=0.998), followed by a linear interpolation of three SPECMAP datums (Table 2) based on the benthic $\delta^{18}O$ 893A record [*Kennett*, 1995]. An average reservoir age of 825 years was applied to the ^{14}C ages as the radiocarbon ages of mussels (*Mytilus californianus*) collected from the Santa Barbara Channel prior to 1950 varied between 720 and 960 years (B.L. Ingram and D.J. Kennett, unpublished data, 1995). Radiocarbon ages were converted to calendar ages using *Stuiver and Braziunas* [1993] (0 to 10.5 kyr) and *Bard et al.* [1993] (>10.5 kyr). All geologically instantaneous events (turbidites and storm layers) [*Behl*, 1995] >10 cm were removed from the linear extrapolation of the age-depth model. Thirteen of the last 16 interstadials identified by the "bioturbation index" at ODP hole 893A differ by 1% in age [*Behl and Kennett*, 1996] to those recorded in the GISP2 ice core record [*Bender et al.*, 1994], thus demonstrating a close relationship between the two records. The paleoclimatic framework (the initiations and terminations of stadials and interstadials) described in this paper is based on climate-induced oscillations in both the bioturbation index and the planktonic $\delta^{18}O$ record (Figure 2) [*Behl and Kennett*, 1996; *Hendy and Kennett*, 1999].

Table 1. Radiocarbon Dates, Void-Corrected Depths, and Corrected Ages for Planktonic Foraminifer Samples

Sample	Void Corrected Depth, mbsf	Average planktonic ^{14}C age, years	Corrected Age S. and B., years B. P.	Corrected Age Bard, years B. P.
1H-3 63-66	3.65	2520	1670	
1H-4 117-120	5.68	3555	2780	
2H-2 71-74	8.88	6200	6190	
2H-4 105-107	11.75	8235	8230	
2H-6 55-57	14.02	9180	9400	
3H-1 87-90	16.82	10280	10790	10812
3H-2 11-14	17.55	10720		11374
3H-2 113-115	18.56	11180		11959
3H-3 112-115	20.01	11830		12781
3H-3 147-150	20.38	11980		12971
3H-5 9-12	20.92	12350		13436
3H-6 96-99	24.09	13130		14411
4H-1 8-11	25.88	14630		16267
4H-3 57-60	29.1	15720		17599
4H-4 3-5	29.99	16260		18254
4H-5 73-76	31.94	18380		20792
5H-7 11-14	43.57	25470		28896

Sample data were taken from *Ingram and Kennett* [1995]. Here mbsf is meters below seafloor, and S. and B. is *Stuiver and Braziunas* [1993].

Table 2. Depths of Oxygen Isotope Events in ODP Hole 893A and Their Ages in Deep-Sea Standard Reference Sequence

Isotope Substage Datum	Void-Corrected Depth, mbsf	Age in SU, kyr
3.13	64.44	43.88
3.30	74.44	50.21
4.00	82.48	58.96

Sample data are from [*Kennett*, 1995].

4. Results

4.1. Planktonic Foraminiferal Faunal Record of ODP Hole 893A

Large variations in planktonic foraminiferal faunal assemblages can be seen in the sequence at ODP hole 893A over a number of timescales (Figure 2). Low-resolution census data have previously been presented showing switches between the dominance of dextral *N. pachyderma* (warm) and sinistral *N. pachyderma* (cool) and sharp oscillations in warm water assemblages (*Orbulina universa* and *Globigerinoides ruber*) over Milankovitch timescales [*Kennett and Venz*, 1995] and during Termination I [*Kennett and Ingram*, 1995]. The high-resolution sampling during MIS 3 demonstrates remarkable planktonic foraminiferal faunal oscillations in Santa Barbara Basin over time intervals of 50 to 70 years or less (Figure 2). These large assemblage changes are clearly correlated to the rapid climate change associated with DO cycles (Figure 2). The response of individual planktonic foraminiferal species to rapid climate change between 60 and 25 ka is described below and displayed in Figure 3.

4.1.1. ***Neogloboquadrina pachyderma*** **(sinistral).** The crystalline, dominantly sinistral (left-coiling) morphotype of *N. pachyderma* was the most prevalent species during stadials, (Figure 2). Sinistral *N. pachyderma* increased in both total (2 to 40 specimens per cm^3) and relative abundance (5 to 60%) during stadials (Figure 3). Similar to the $\delta^{18}O$ record, higher climate variability is suggested during interstadials, for example interstadial (IS) event 12 appears to have several brief (>200 years) incursions of the dominantly sinistral *N. pachyderma* assemblage (Figure 3). Significant variation in the test of the *N. pachyderma* sinistral morphotype was observed during MIS 3,

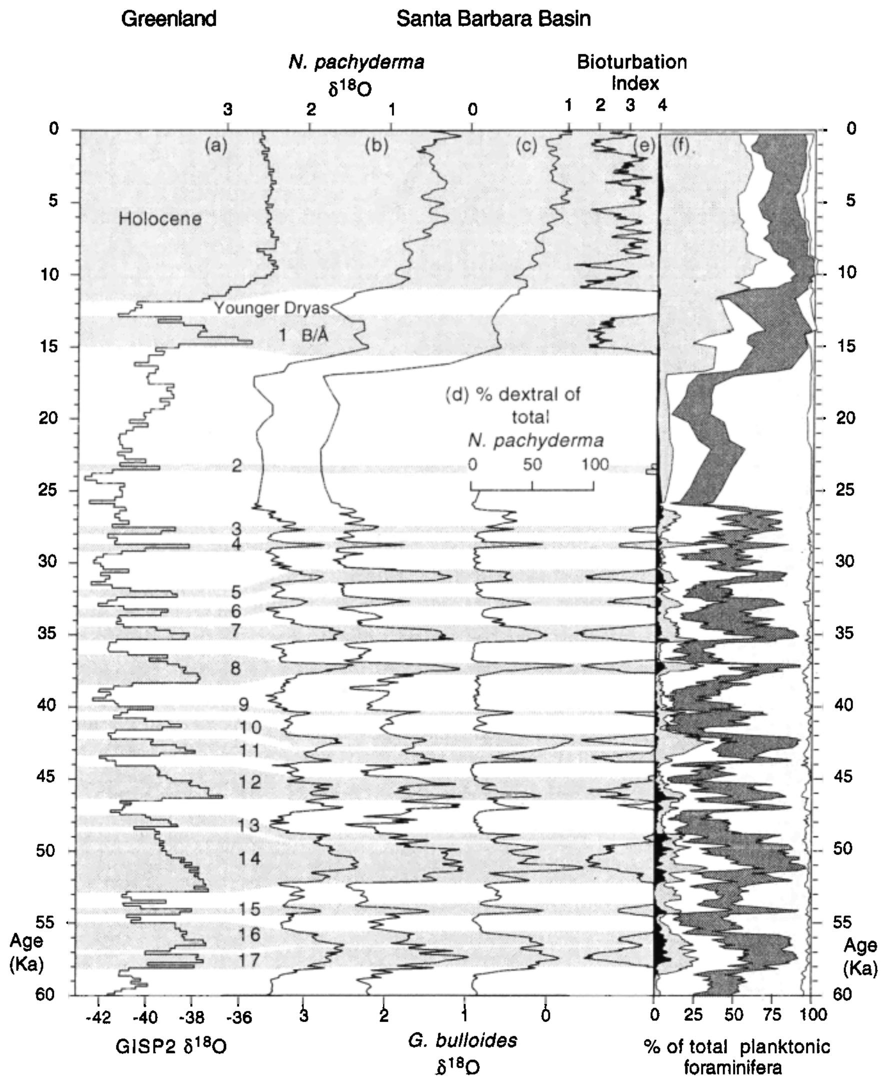

Figure 2. Correlations between GISP2 $\delta^{18}O$ (SMOW) isotope time series [*Bender et al.*, 1994] and planktonic foraminiferal and ventilation time series for ODP hole 893A (Santa Barbara Basin) for the last 60kyr (figure 2a). These include the $\delta^{18}O$ (PDB) records of (b) thermocline-dwelling planktonic foraminifer *N. pachyderma* and (c) surface water planktonic foraminifer *G. bulloides* and from 25 to 60ka [*Hendy and Kennett*, 1999], (d) the ratio of dextral to sinistral coiled *N. pachyderma* (as shown by percent dextral *N. pachyderma*). Also, (e) the 893A bioturbation index [*Behl*, 1995], where on a continuum, 1 indicates laminated sediment facies and 4 indicates massive bioturbated sediment facies. (f) Finally, the percent composition of the total planktonic foraminiferal assemblage, species from left to right: *G. scitula*, *N. pachyderma* (dextral), *G. bulloides*, *G. quinqueloba*, *N. pachyderma* (sinistral), and other species. Changes in all of these parameters clearly define the Dansgaard-Oeschger (DO) climate oscillations (numbers 17-3) during MIS 3 and the Bølling/Allerød. Gray bands represent warm intervals (interstadials and the Holocene). Interstadials (DO events) are numbered according to GISP2 scheme.

varying from heavily calcified, small specimens to large, high-spired, lightly calcified specimens. Not presently found in southern Californian surface water [*Sautter and Thunell*, 1991], this species inhabits cool waters between 6° and 8°C at 50°N with little or no thermocline and high surface nutrient concentrations [*Reynolds and Thunell*, 1986]. Sinistral *N. pachyderma* has been found in surface water as warm as 10°C in southern Oregon, in association with seasonal upwelling and increased transport of subarctic water in the California Current [*Ortiz and Mix*, 1992].

4.1.2. ***Neogloboquadrina pachyderma*** **(dextral).** Dextral (right-coiling) *N. pachyderma* increases both in total abundance (1 to 30 specimens per cm^3) and percent abundance (1 to 50%) at interstadial initiations to dominate during these warm rapid climate events (Figure 3). IS 12 appears anomalous in exhibiting low abundances of dextral *N. pachyderma*. Covariance in faunal and isotopic *N. pachyderma* records within interstadial episodes (except IS 12) is predictable since both proxies reflect changes at the thermocline (Figure 3). The dominantly dextral, reticulate morphotype of *N. pachyderma* found at or below the thermocline in 8° to 14°C waters prefers conditions when the upper water column is moderately stratified [*Sautter and Thunell*, 1991; *Reynolds and Thunell*, 1986].

4.1.3. ***Globigerina bulloides.*** *Globigerina bulloides* was dominant during interstadials, increasing relative abundance from

5 to up to 70% (Figure 3). During interstadials, large variations in total abundance (2 to 60 specimens per cm^3) of *G. bulloides* suggest brief "bloom" intervals (Figure 3). Although not quantified, morphological differences in *G. bulloides* occurred between stadials and interstadials. Specimens from cool intervals were small and thickly calcified, with small apertures, while those from interstadials were larger and thinly calcified, with open apertures. A eurythermal species found in the surface mixed layer of waters ranging in temperature between 6° and 26°C, *G. bulloides* is most dominant in cool subtropical/ transitional upwelling conditions [*Sautter and Thunell*, 1991].

4.1.4. *Globigerina quinqueloba*. *Globigerina quinqueloba* was present in relatively high numbers during stadials but increased total abundance (4 to 30 specimens per cm^3) during interstadials. As a result the relative abundance of this species appears less variable than other species ranging from 30 to 60% (Figure 3). *Globigerina quinqueloba* is a eurythermal species, found in the surface mixed layer of 5° to 20°C water and often associated with dextral *N. pachyderma* and *G. glutinata*. It has been observed to increase production during spring and diatom blooms [*Sautter and Thunell*, 1991].

4.1.5. *Globigerinita glutinata*. *Globigerinita glutinata* remained low in total abundance throughout MIS 3 but increased in relative abundance (2 to 10%) during stadials (Figure 3). *Globigerinita glutinata* is a eurythermal species often found in association with sinistral *N. pachyderma* [*Reynolds and Thunell*, 1986] in the deep, surface mixed layer, regardless of thermal structure or temperature (6° to 25°C), and is associated with high productivity [*Sautter and Thunell*, 1991].

4.1.6. *Globorotalia scitula*. The relative abundance of *G. scitula* was highest during interstadials making up ~10% of the assemblage (Figure 3). A unique feature of this record is that this species also experienced unusually high production (increasing by ~10 specimens per cm^3 or ~25% of the relative abundance) during the earlier interstadials (60 to 45 ka) (Figure 3) giving the appearance of "blooms." A deep-dwelling, subarctic species, *G. scitula* is possibly associated with the subducted shallow salinity minimum in the North Pacific but not with upwelling [*Ortiz et al.*, 1996].

The Santa Barbara Basin planktonic foraminiferal record shows no evidence of dissolution effects during either interstadials or stadials of MIS 3. The continuous relatively high abundance down core of highly solution-susceptible species such as *G. quinqueloba* [*Coulbourn et al.*, 1980] and perfect preservation of extremely delicate specimens (Figure 3) suggest that dissolution of carbonate in the basin was insignificant. As a result, assemblage shifts cannot be attributed to changes in corrosiveness of bottom waters associated with switches in intermediate water source [*Kennett and Ingram*, 1995; *Behl and Kennett*, 1996]. Indeed, the excellent preservation of foraminifera specimens at ODP hole 893A may result in an assemblage which has no analog with Eastern Pacific core top foraminifera census data.

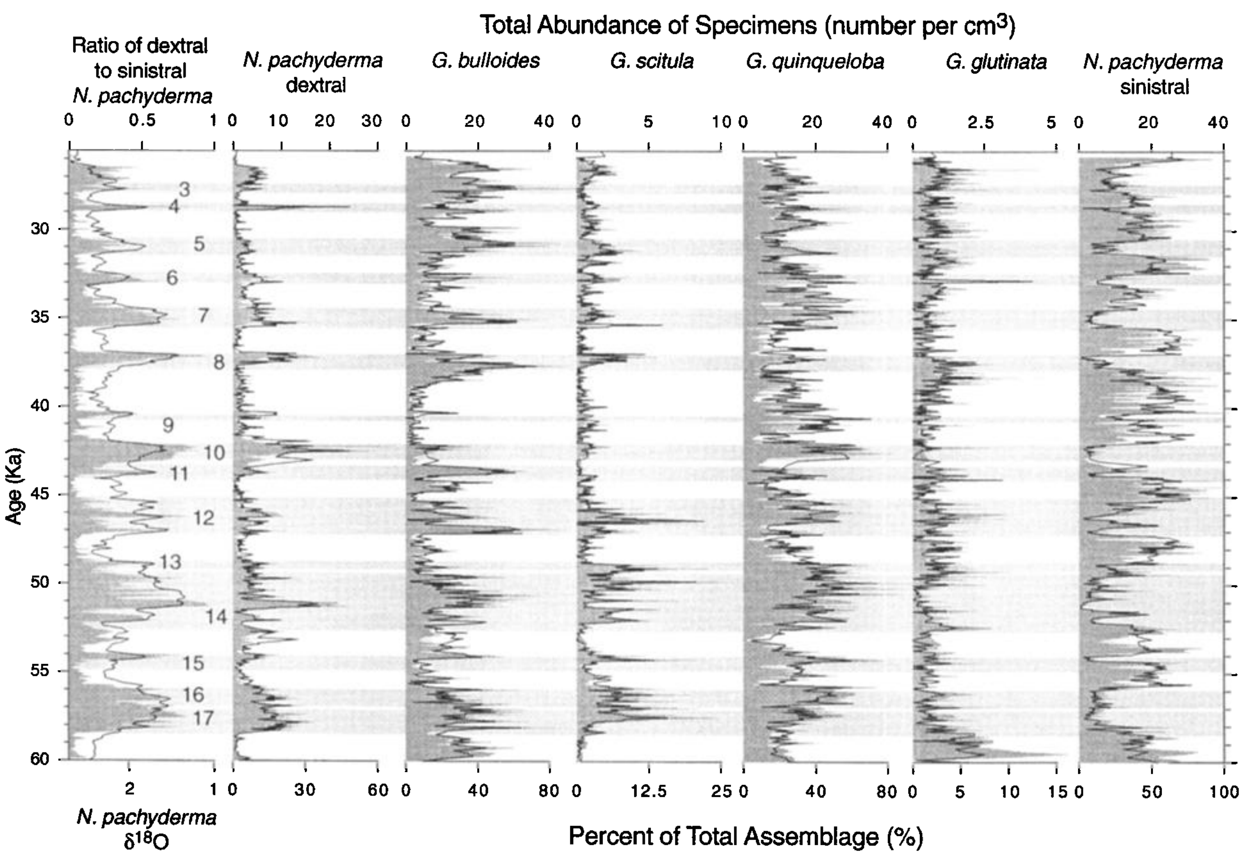

Figure 3. ODP hole 893A, Santa Barbara Basin, planktonic foraminiferal assemblage relative abundance or percentage of assemblage (black lines) and total abundance or total number of specimens (dark shaded areas) for 60 to 25ka compared to the coiling ratio and $\delta^{18}O$ of *N. pachyderma* [*Hendy and Kennett*, 1999]. Gray bands represent warm intervals (interstadials and the Holocene). Interstadials (D-O events) are numbered according to GISP2 scheme.

4.2. Factor Analysis of the Assemblages

The objective of creating a Q mode factor model is to explain interrelationships in a multivariate database by the presence of a few factors to reveal the simple underlying structure [*Davis*, 1973]. Thus the changes in the faunal composition are simplified to changes in factor loadings. Factor analysis of the assemblages at ODP hole 893A statistically confirms two distinct groupings of planktonic foraminiferal species accounting for 82% of the total variance. Communalities are mostly <0.8, showing that factor groupings well describe the data set. These two groupings closely correlate with the rapid climate change as represented by planktonic $\delta^{18}O$ records (Figure 4). The factors are distinguished as follows: (1) Samples (47.1% of the faunal variance) from stadial events show the highest loading onto this factor because of the importance of sinistral *N. pachyderma*, with some influence by *G. quinqueloba* and *G. glutinata* (Table 3). Thus factor 1 is interpreted as the cool or stadial assemblage. (2) Samples (34.6% of the faunal variance) occurring within the interstadials show the highest loadings onto this factor due to the importance of dextral *N. pachyderma, G. bulloides, G. quinqueloba,* and *G. scitula.* Minor contributions are made by subtropical species such as *Orbulina universa* and *G. ruber* (Table 3). Factor 2 is interpreted as the interstadial or warm assemblage.

Both factor analysis and the abundances of individual planktonic foraminiferal species suggest rapid climate change associated with the DO cycles during MIS 3. The relative abundance of the planktonic foraminifera species and sample loadings along factors 1 and 2 changed at similar rates (<50 to 70 years) as the shifts in planktonic foraminiferal $\delta^{18}O$ At the initiation of warmings, a significant ~5 to 90% shift in warm (dextral) to cool (sinistral) forms of *N. pachyderma* occurred as rapidly as the isotopic shifts (Figure 3). Variability during interstadials not evident during stadials is a feature of both the planktonic $\delta^{18}O$ record and the planktonic foraminiferal assemblages. Brief cool intervals (50 to 150 years) inferred by $\delta^{18}O$ records that interrupted longer duration interstadials are confirmed by planktonic faunal census data. For example, two major cool intervals during IS 12 (45.5 and 46.5 ka) inferred by the planktonic $\delta^{18}O$ record are also reflected in factor analysis results (Figure 4). Similarly close correlation between the planktonic $\delta^{18}O$ records and planktonic foraminiferal assemblage is demonstrated during the cool interval separating IS 13 and 14 (49.2 ka) (Figures 2 and 4).

Table 3. Varimax Factor Score Matrix

Variables	Factor 1	Factor 2
G. quinqueloba	0.2322	0.6047
G. bulloides	0.0684	0.5740
N. dutertrei	-0.0155	0.0439
G. scitula	0.0115	0.2481
G. ruber	-0.0164	0.0678
Orbulina universa	-0.0192	0.0795
G. digitata	-0.0050	0.0246
G. glutinata	0.1783	0.1486
G. falconesis	-0.0176	0.0805
G. uvula	-0.0010	0.1176
Dextral *N. pachyderma*	-0.1043	0.3975
Sinistral *N. pachyderma*	0.9473	-0.1716

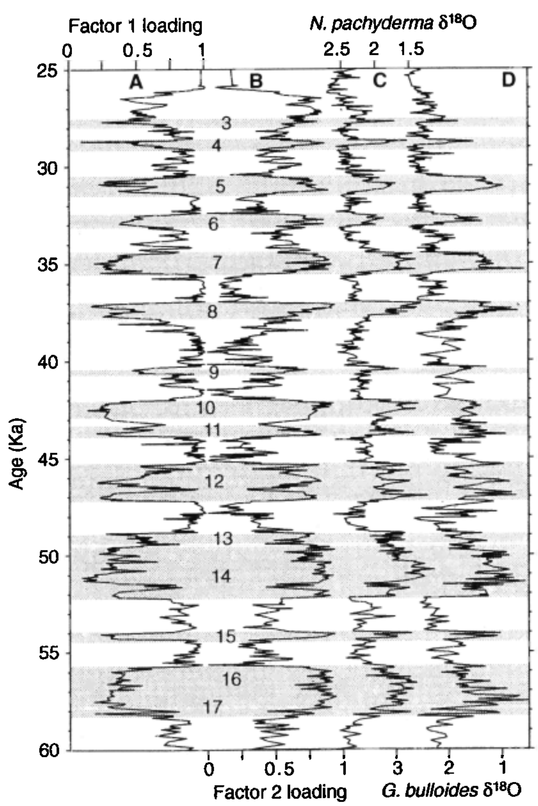

Figure 4. Comparison of (a) factor 1 and (b) factor 2 loadings with (c) the $\delta^{18}O$ records of *N. pachyderma* and (d) *G. bulloides* [*Hendy and Kennett*, 1999].

5. Planktonic Foraminiferal Temperature Estimates at ODP Hole 893A

Independent of $\delta^{18}O$, planktonic foraminiferal faunal assemblage derived temperatures (via transfer functions and MAT) can provide verification of temperatures estimated by isotopes. We have produced SSTs during the last 5 ka of the Holocene to evaluate how well reconstructed temperature estimates agree with expected temperatures for Santa Barbara Basin. Results of these comparisons are displayed in Figure 5 and Table 4 and discussed in the sections 4.1, 4.2, and 4.3.

5.1. SSTs Based on Stable Isotopic Analysis

Temperatures presented in Figure 5a were derived from $\delta^{18}O$ signals using the *Craig* [1965] equation. Salinity in the basin (33.6) [*Lynn and Simpson*, 1987] was converted using a North Pacific δ_W-salinity relationship [*Zahn et al.*, 1991], and an estimated ice volume of 1.1‰ [*Chappell and Shackleton*, 1986; *Schrag*, 1996] was incrementally removed or added based on the SPECMAP global isotope curve [*Martinson et al.*, 1987]. Temperatures (10° to 15°C) recorded at 25 m depth in the modern Santa Barbara Basin [*Thunell*, 1998] close to the depth at which the surface-dwelling species (*G. bulloides*) secretes its test are similar to temperatures produced by *N. pachyderma* (11° to 13°C)

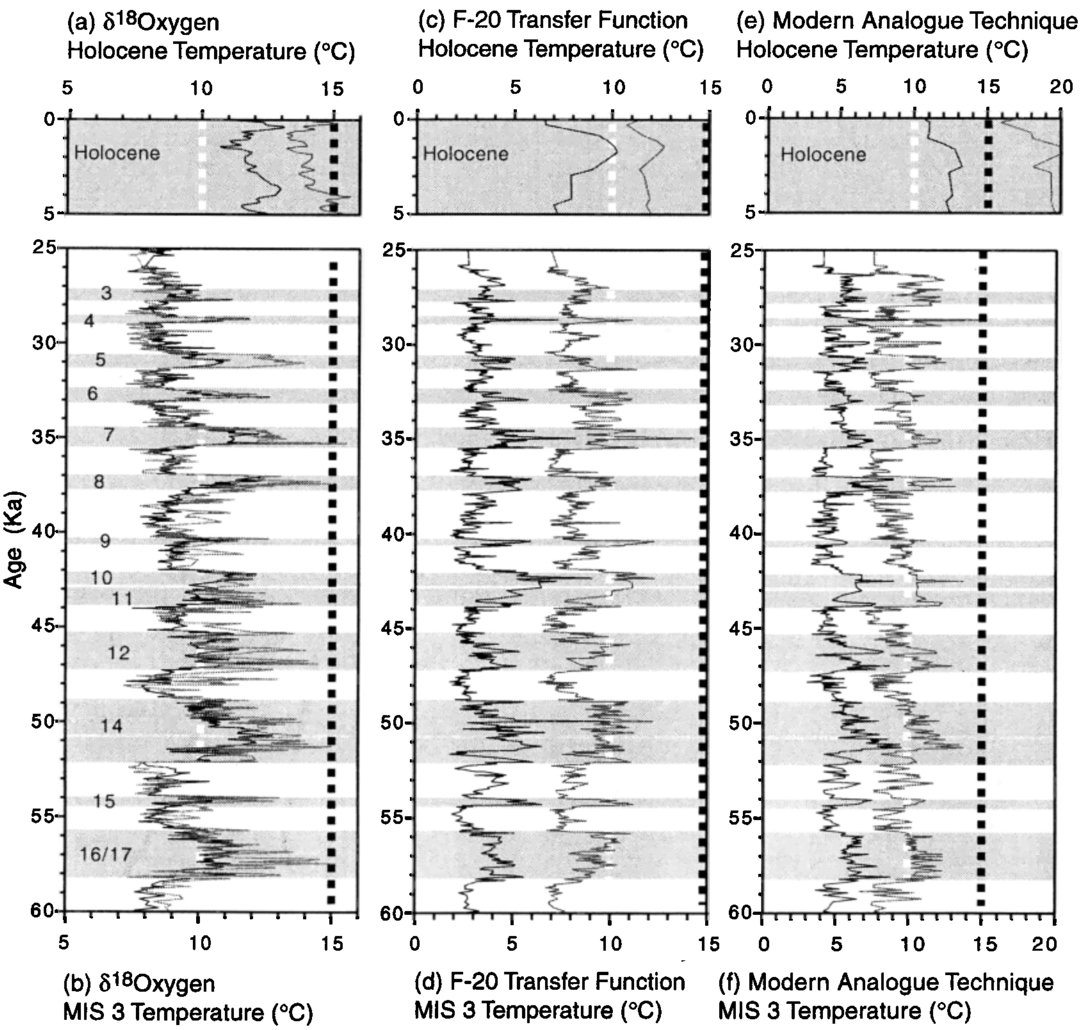

Figure 5. ODP hole 893A temperature estimates for 5 ka to present and 60 to 25 ka comparing SST derived using three different methods, all based on planktonic foraminiferal assemblages with SST based on $\delta^{18}O$ records of *G. bulloides* and *N. pachyderma* using the *Craig* [1965] equation for (a) the Holocene and (b) MIS 3. SST using the F-20RSC Transfer Function equation based on planktonic foraminiferal assemblages for (c) the Holocene and (d) MIS 3. Summer temperatures are represented by the shaded line, and winter temperatures are represented by the black line. SST the modern analog technique based on planktonic foraminiferal relative abundance using only 12 species found in the basin for (e) the Holocene and (f) MIS 3. Summer temperatures are represented by the grey line and winter temperatures are represented by the black line. Gray bands represent warm intervals (interstadials and the Holocene). Interstadials (D-O events) are numbered according to GISP2 scheme. Heavy, dashed lines represent coolest (white) and warmest (black) temperatures at 25 m depth in the Santa Barbara Channel presently [*Thunell*, 1998].

and *G. bulloides* (13° to 16°C) during the last 5 ka (Figure 5a and Table 4). The MIS 3 results are summarized in Table 4 and show that the $\delta^{18}O$ estimated thermocline temperature shift between stadials and interstadials was ~3°C, while at the surface the shift was ~5° to 6°C (Figure 5b).

5.2. SSTs Based on Transfer Functions

Pioneered by *Imbrie and Kipp* [1971], the transfer function method of reconstructing paleoenvironments has provided geologists with an estimate of a physical variable (i.e., SST) from faunal census data. The F-20RSC transfer function, an Atlantic equation updated for use in the Pacific [*Molfino et al.*, 1982; *Prell*, 1985], estimated cooler temperatures than expected in Santa Barbara Basin during the last 5 kyr with winter temperatures of ~7° to 10°C and summer temperatures of ~11° to 13°C (Figure 5b). Transfer function temperature estimates during MIS 3 also appeared very cool (Figure 5d and Table 4). Temperature shifts between stadials and interstadials estimated by the transfer function technique varied between 2° and 5°C (Figure 5d). Differences are large between SSTs estimated by the F-20RSC transfer function method and the $\delta^{18}O$ derivation during both the last 5 kyr and MIS 3 (Table 4). These results suggest the transfer function method systematically underestimates temperatures in Santa Barbara Basin by as much as 5°C. Therefore, despite the high communality (0.8 to 0.9) of the 893A samples compared to the matrix, the environmental conditions experienced by the Santa Barbara Basin foraminiferal assemblage probably do not reflect those of the coretop samples used.

Table 4. Comparison of Temperature Reconstructions During the Last 5 kyr and Interstadials and Stadials of MIS 3 Based on $\delta^{18}O$ Values, the F-20RSC Transfer Function, and Modern Analog Technique (MAT 12 Species)

	$\delta^{18}O$ temperature			F-20RSC Transfer Function Temperature			MAT (12 species) Temperature		
Time Interval	Species	Range, °C	Average, °C	Season	Range, °C	Average, °C	Season	Range, °C	Average, °C
Holocene	*G. bulloides*	14 - 16	14	Summer	11 – 13	11.5	Summer	16 – 20	18
	N. pachyderma	12 – 13	12	Winter	7 – 10	8	Winter	11 – 13	12
Interstadials	*G. bulloides*	11 - 15	13	Summer	9 – 12	10	Summer	10 – 14	11
	N. pachyderma	10–12.5	11.5	Winter	4 – 7	5	Winter	6 – 9	7
Stadials	*G. bulloides*	7.5 – 10	9.5	Summer	7 – 8.5	8	Summer	8 – 10	9
	N. pachyderma	8 – 9.5	9	Winter	2 – 4	3	Winter	4 – 6	5

5.3. SSTs Based on Modern Analog Technique (MAT)

The modern analogue technique (MAT) compares the relative abundances of species in the down-core assemblage with a global calibration database [*Hutson*, 1980; *Prell*, 1985] of >1000 coretops from which the 10 most similar analogs are selected using the squared-chord dissimilarity measurement. As the planktonic foraminiferal assemblage at ODP hole 893A is of low diversity, we were interested in the MAT technique response to assemblages of decreasing diversity. Therefore we compared SST estimates produced by 35 MAT species with those obtained when only the 12 species found at the site are included and, finally, with those when only the dominant 6 species are included (Table 5).

The results suggest that the derived SSTs produce temperature estimates most similar to the two other methods (transfer function and $\delta^{18}O$) (Table 4). The $\delta^{18}O$ estimated temperatures of *G. bulloides* and *N. pachyderma* closely follow summer SSTs of the 12-species derivation of MAT, displaying the 4° to 6°C temperature shift between stadials and interstadials (Figure 5b and 5f) but are several degrees warmer than the transfer function-derived SST (Figure 5d and 5f). The dissimilarity of the 893A Santa Barbara Basin samples compared to the database remained low through all experiments, suggesting that assemblages at the site were not anomalous with respect to assemblages from the database.

The anomalously cool winter SST results may also be an artifact of sieve size since the 125 μm sieve was employed rather than the standard 150 μm size. Although no systematic dependence on sieve size (125 versus 150 μm) was detected by *Ortiz and Mix* [1997a], as a test we generated census data for both sieve sizes using 10 randomly picked samples (summarized in Table 6). Tests revealed no consistent differences between sieve sizes, although the 125 μm sieve summer temperatures were warmer by 0.35°C when the MAT technique was applied. The 125 μm sieve MAT temperature estimates varied by ~0.5°C, which is relatively insignificant compared to the temperature differences between stadial and interstadial episodes.

6. Discussion

The planktonic foraminiferal assemblage of Santa Barbara Basin associated with stadials resembles Last Glacial Maximum assemblages found in other regions of the North Pacific [*Ortiz and Mix.*, 1997b; *Mortyn et al.*, 1996] being dominated by *N. pachyderma* (sinistral), *G. quinqueloba*, and *G. glutinata* (Figure 2). Another assemblage marked by higher diversity was associated with the interstadials and was dominated by *G. bulloides, N. pachyderma* (dextral), *G. scitula, G. quinqueloba, Orbulina universa*, and *G. ruber* (white) (Figure 2). No other North Pacific records with sufficient resolution to distinguish interstadials are yet available for comparison with the interstadial assemblage found at ODP hole 893A.

Although temperature undoubtedly played a major role in the planktonic foraminiferal distribution during this time period, these assemblages have other environmental and biotic factors in

Table 5. Comparison of MAT Temperature Reconstructions During the Last 5 kyr and Interstadials and Stadials of MIS 3 Using 35, 12, and 6 Species

	MAT (35 species) Temperature, °C		MAT (12 species) Temperature, °C		MAT (6 species) Temperature, °C	
Time Interval	Range, °C	Average, °C	Range, °C	Average, °C	Range, °C	Average, °C
Holocene						
Summer	14 – 23	19	16 – 21	19	18 – 22	20
Winter	9 – 15	12	11 – 13	12	12 – 14	13
Interstadials						
Summer	10 – 14	11	10 – 14	12	10 – 21	14
Winter	4 – 9	6	6 – 9	7	5 – 17	10
Stadials						
Summer	7 – 9	8.5	8 – 11	9	7 – 13	9
Winter	3 – 6	5	4 – 6	5	3 – 8	5

Table 6. Comparison of Results From 10 Random Census Counts Using 125 and 150 μm Sieves for Planktonic Foraminiferal Census Temperature Estimates From ODP Hole 893A

	Modern Analog Technique		Transfer Function F-20RSC	
Sample	Winter Temperature Difference (150 - 125 μm)	Summer Temperature Difference (150 - 125 μm)	Winter Temperature Difference (150 - 125 μm)	Summer Temperature Difference (150 - 125 μm)
5H-7 42 -44	-1.14	-0.14	-0.21	0.12
6H-4 96 -98	0.41	0.26	-0.20	-0.29
6H-6 19 -21	0.46	0.18	0.00	0.04
7H-3 41 -43	-0.64	0.31	0.00	0.08
8H-4 50 -52	0.02	1.02	0.10	0.29
8H-5 106 -108	0.00	0.00	0.10	0.36
8H-7 41 -43	0.57	1.46	-0.21	0.25
9H-1 27 -29	-1.21	-0.38	0.27	0.57
9H-5 55 -57	0.47	0.66	-0.23	-0.29
9H-7 59 -61	-0.50	0.07	0.07	0.15
Average Difference	0.16°C cooler	0.34°C warmer	0.03°C cooler	0.13°C warmer
Average Variance	0.54°C	0.45°C	0.14°C	0.24°C

common. The low-diversity Santa Barbara Basin assemblage is characterized by opportunists presently associated with seasonally variable regions with wide temperature ranges (5° to 25°C) and moderate to high nutrient availability [*Reynolds and Thunell*, 1986; *Sautter and Thunell*, 1991]. Suggestive of a biotic community that is adapted to frequent environmental disruption, it is possible that the strong instability in the California Current System, and perhaps local upwelling, was a major control on the evolution of highly tolerant, opportunistic planktonic foraminifera in the region.

6.1. Sea Surface Temperature Reconstruction in Santa Barbara Basin

Accurate SST reconstructions are necessary in understanding the response of the surface ocean to and determining causes and feedbacks of global climate change, as well as providing critical boundary conditions for the modeling of climate forcing and responses. SST reconstructions from California margin cores over the last glacial-interglacial cycle have produced conflicting results. Planktonic foraminiferal assemblage and isotopic based SST reconstructions suggest a 5° to 10°C temperature shift over the last glacial-interglacial transition in the California borderland [*Kahn et al.*, 1981; *Kennett and Venz*, 1995; *Mortyn et al.*, 1996]., while some U_K^{37} SST estimates suggest much smaller glacial-interglacial temperature shifts (1° to 2°C) [*Doose et al.*, 1997; *Herbert et al.*, 1995].

Changes in planktonic faunal assemblages provide critical evidence that temperature was the major contributor to $\delta^{18}O$ shifts during the interstadial-stadial switches. SST values during MIS 3 produced by foraminiferal census techniques appear to underestimate the winter SSTs. Difficulties estimating SSTs in some regions of the ocean using the MAT and particularly the transfer function method have previously been recognized. *Ortiz and Mix* [1997b] found that transfer function-derived SST from surface sediments under the California Current exhibited severe errors when compared to MAT-derived SST and Levitus data. As many California Current surface sediments indicate heavy carbonate dissolution, error may result when using samples from these core top sediments in the derivation of equations [*Le and Shackleton*, 1994]. The method may also unrealistically calibrate SSTs with species that live at depth or respond to other oceanic variables such as nutrient availability and thermocline depth [*Andreasen and Ravelo*, 1997; *Ottens and Nederbragt*, 1992].

The high-latitude North Atlantic location of analogs of ODP hole 893A samples selected by the MAT method produced the anomalously cool winter SSTs. Similarity between these locations and Santa Barbara Basin is unlikely to be temperature related. The low planktonic foraminiferal diversity within the California Current (for example, the paucity of the subtropical planktonic foraminifer *G. inflata*) is also a characteristic of high-latitude core top samples. Reducing the number of species used in the comparison created a database with a similar (though artificial) low diversity to Santa Barbara Basin. Finally, the near-shore aspect of the basin may result in assemblages experiencing different environmental conditions to their analogs. Compared to open ocean sites of the core top database, sediments are unusually well preserved, and Santa Barbara Basin is affected by coastal phenomena such as upwelling.

Both MAT and transfer function techniques suggest ~3° to 5°C SST shifts occurred between stadials and interstadials, and estimated summer temperatures were similar (within 1°C) to those estimated by the thermocline dwelling *N. pachyderma*. Therefore the planktonic foraminiferal assemblage supports large-magnitude SST shifts in Santa Barbara Basin during rapid climate change and suggests salinity shifts (<0.5‰) were minor. The $\delta^{18}O$ estimated SSTs might be biased by other environmental variables such as depth habitat and the growth season, which affect individual specimens. Sediment trap studies show that the largest flux of *N. pachyderma* and *G. bulloides* tests to the basin floor occur during late summer, although both species are present in the basin throughout the year [*Pak et al.*, 1997]. Despite these environmental variables, $\delta^{18}O$-estimated temperatures appear to produce the most realistic reconstruction of SST.

6.2. Causes of Sea Surface Temperature Shifts in Santa Barbara Basin

The very cool temperatures (~7° to 8°C) during stadial events of MIS 3 (Figures 5b, 5d and 5e) suggest a major increase in the advection of subarctic waters in the region. It has been suggested that the California Current intensified during the last glacial episode increasing the influence of subarctic water into the region (Figure 6) [*Thunell and Mortyn*, 1995]. At the same time, geostrophic flow between San Diego and Point Conception may have been weaker or absent, reducing the northward transport of subtropical water into the basin via the Borderland Gyre and therefore the California Countercurrent. The combined result of changes in the relative strengths of these two currents led to decreased SST's in Santa Barbara Basin. Conversely, during interstadials the California Current weakened, the Countercurrent strengthened, and the Borderland Gyre was reestablished, increasing advection of subtropical water into the basin relative to subarctic water (Figure 6). Consequently, warming of the SSTs in the region was magnified by changes in the relative contributions of surface water masses transported via currents.

In addition to changes in the relative strengths of currents within the region, several other processes might also have contributed toward reduced SSTs in the record. Presently, upwelling off Point Conception (Figure 1) is a significant

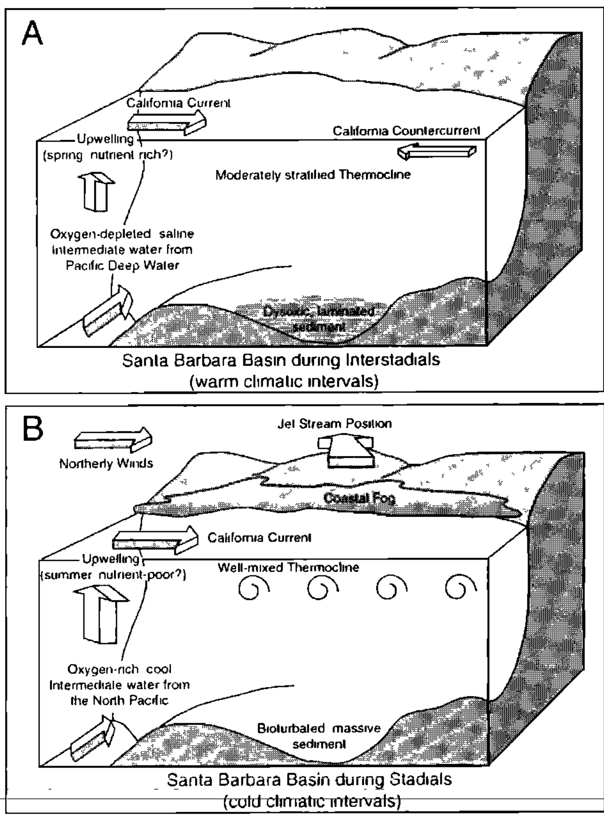

Figure 6. Schematic block diagram of the oceanography of Santa Barbara Basin during the bimodal climatic states which occurred MIS 3. Figure 6a represents warm interstadial events, while Figure 6b represent cool stadial events.

contributor to cooling of SSTs during spring in the basin [*Hendershott and Winant*, 1996]. Local surface hydrology is affected as upwelled water is transported into the Santa Barbara Channel by the California Current [*Hendershott and Winant*, 1996]. Increased upwelling intensity during the cool episodes of the MIS 3 would also depress SSTs in the region, particularly close to the source of the upwelling. This hypothesis can be tested using records located beneath the upwelling cell at Point Conception (such as ODP site 1017).

The season of the year when upwelling occurs may also effect Santa Barbara Basin SSTs. If, during stadials, the period of predominately northerly winds occurred in summer, SSTs would be depressed during the season when radiative heating of surface water usually occurs, creating elevated surface temperatures and a stable, stratified upper water column. This scenario is similar to that suggested by both the $\delta^{18}O$ record and the planktonic foraminiferal assemblage in Santa Barbara Basin during stadials. Increased sea fog produced during upwelling might contribute to the cooler air temperatures and increased effective precipitation of the last glacial suggested by the pollen record [*Heusser*, 1998].

Another process involved in rapidly changing surface water temperatures was *in situ* atmospheric heating. Warm SST overshoots of up to 3°C during several interstadial events are displayed in the surface $\delta^{18}O$ record and have been suggested to imply amplification of climatic warming [*Hendy and Kennett*, 1999]. The absence of subtropical species in the planktonic foraminiferal assemblage during these warmings suggests that the overshoots were not produced by increased advection of subtropical surface water masses. Rather, this phenomenon might have been produced by a top-down warming such as might occur, for example, if coastal sea fog cover was reduced in the region, particularly during summer, allowing increased radiative warming of the surface waters. Alternatively, greenhouse gas increases [*Chappellaz et al.*, 1993; *Broecker*, 1997] might also have produced atmospheric warming and cannot be dismissed by our results.

6.3. Bimodality of the Surface Hydrology of Santa Barbara Basin

Two distinct states of upper water column hydrology in Santa Barbara Basin during MIS 3 are apparent from the planktonic $\delta^{18}O$ records and factor analysis of the planktonic foraminiferal assemblage, representing separate organizational modes of surface ocean circulation. The bimodality of the planktonic assemblages suggests environmental parameters in addition to SST affected the upper water column of the basin. Distinction between the two modes of surface circulation in the region follows: The stadials were characterized by cool SSTs, a shallow thermocline, and low diversity of planktonic foraminifera, and interstadials were characterized by warm SSTs, a moderately stratified upper water column, and higher diversity.

During stadials, Santa Barbara Basin appeared to have a shallow thermocline and well-mixed surface waters (Figure 6). Supporting evidence includes the similarity of *N. pachyderma* and *G. bulloides* $\delta^{18}O$ values during stadials, and an abundance of sinistrally coiled *N. pachyderma* in the planktonic foraminiferal assemblage. Dominance of subarctic species during this time suggests increased advection of subarctic water into Santa Barbara Basin, attributed to a stronger California Current. As historic interdecadal variation (~50 m) in thermocline depth within the California Current System is well correlated with climatically driven changes in current strength [*McGowan et. al.*, 1998; *Weinheimer et al.*, 1999], a shallow stadial thermocline might also be a result of increased current strength.

The water column structure of Santa Barbara Basin during interstadials suggests increased vertical structure, i.e., a steeper vertical temperature gradient and deeper thermocline (Figure 6). During interstadials the difference between the $\delta^{18}O$ of *N. pachyderma* and *G. bulloides* increases by up to 0.8‰ (Figure 2), supporting increased vertical structure. Furthermore, foraminiferal assemblages are dominated by species that prefer moderately stratified conditions, including dextral *N. pachyderma*, *G. scitula*, *O. universa*, and *G. ruber* (white) [*Reynolds and Thunell*, 1986]. The $\delta^{18}O$ record and the planktonic foraminiferal record suggest the interstadial thermocline was shallower and SSTs were several degrees cooler than during the Holocene, so modern circulation can not be used an analog.

G. scitula is a deep dwelling species associated with subarctic water masses [*Ortiz et al.*, 1996]; however, in the ODP hole 893A record this species significantly increased abundance during interstadial events. This result is unexpected, as advection of subarctic water decreases during interstadials. Because deep-dwelling organisms are not strongly influenced by surface warming such as occurred during interstadials, we attribute the unusual abundance of *G. scitula* during interstadials to a change in water column structure rather than temperature. Deep-dwelling *G. scitula* is inferred to be responding to a stratified thermocline with a corresponding increased nutrient availability with depth.

There appears to be little inertia in switching between these two modes of ocean and atmospheric circulation. The evidence for rapid climate change from Santa Barbara Basin demonstrates that the global climate system was bistable during MIS 3. Surface ocean circulation off the Southern California coast behaved in a nonlinear fashion as the global climate conditions were positioned close to a threshold. When the climate system was pushed beyond this threshold, surface ocean circulation in the region abruptly reorganized from one stable mode to the other, forced by the reorganization of atmospheric circulation over the Northeast Pacific.

6.4. Reorganization of North Pacific Atmospheric Circulation

Surface ocean circulation in the North Pacific is intimately related and responds rapidly to changes in atmospheric circulation over the North Pacific. Atmospheric circulation over the northeast Pacific (the Aleutian Low and the North Pacific High) has been shown to play a major role in the decadal-scale anomalous surface circulation of the North Pacific Oscillation when the California Current weakens as the Aleutian Low expands [*McGowen et al.*, 1998]. This close relationship between atmospheric and ocean circulation in the northeast Pacific is supported by behavior of the surface hydrology in the Santa Barbara Basin record during DO events.

The possible effects of atmospheric reorganization in the North Pacific have been demonstrated in modeling of the Last Glacial Maximum by the *COHMAP members* [1988] and suggest an intensified Aleutian Low and an equatorward displaced North Pacific High. Enhanced Aleutian Low circulation similar to that of the North Pacific Oscillation [*McGowan et al.*, 1998] (and presented here as a model of stadial circulation) would increase circulation of surface water into the Aleutian Gyre and, consequently, the subarctic component of North Pacific circulation. Ultimately cool (recent SST estimates for the last glacial Aleutian Gyre suggest 0° to 4°C [*de Vernal and Pedersen*, 1997]), fresh, low-nutrient water [*Reid et al.*, 1958] would be recirculated into the West Wind Drift and the California Current.

The rapid switching of SST temperatures in the southern California region also demonstrate California Countercurrent and Borderland Gyre instability. Though not directly linked to atmospheric circulation in the northeast Pacific as is the case for the California Current, the gyre is enhanced by a locally formed geostrophic gradient established in fall and winter after seasonal upwelling and radiative heating in the region creates a steep temperature gradient between Point Conception and San Diego [*Winant and Dorman*, 1997]. As predominant northerly winds relax, upwelling diminishes, and the influence of the California Current is reduced, the relative importance of the Countercurrent in the region increases with the establishment of the California Borderland Gyre [*Reid et al.*, 1958].

During stadials, increased subarctic water was transported onto the Southern California Margin by the California Current and summer sea surface heating diminished by upwelling, resulting in a reduced temperature gradient between Point Conception and San Diego. In this regime, the Borderland Gyre, had little chance to establish a strong geostrophic flow, and the relative influence of the California Countercurrent in the region was diminished. Conversely during interstadials the gyre could reestablish flow during stable stratified periods of elevated SST, similar to the present (Figure 6). As the California Countercurrent is an important factor in the advection of subtropical water into the basin presently, the strength of this current would also assist in rapidly increasing or decreasing SST in the basin, which is supported by ODP hole 893A planktonic $\delta^{18}O$ and assemblage results.

Reorganization of the North Pacific atmospheric circulation would not only affect surface currents but also upwelling regimes along the North America West Coast. Presently upwelling off Point Conception occurs during the spring when northerly winds prevail as the North Pacific High moves north after winter [*Hendershott and Winant*, 1996]. Southward movement of the North Pacific High during the Last Glacial Maximum reduced upwelling along the Oregon coast [*Lyle et al.*, 1992; *Ortiz and Mix*, 1997a] and appears to have enhanced upwelling in Southern California [*Lyle et al.*, 1992; *Mortyn and Thunell*, 1997]. During interstadial events a poleward movement of the North Pacific High and a contraction of the Aleutian Low created upwelling conditions similar to the present (Figure 6).

7. Conclusions

Planktonic foraminiferal census data have now been presented for ODP hole 893A (Santa Barbara Basin) during the full sequence of DO cycles from 60 to 25 ka. Two distinct assemblages, confirmed by Q mode factor analysis, have been identified. During stadials, planktonic foraminiferal assemblages were dominated by sinistral *N. pachyderma*, while during interstadials, assemblages were dominated by *G. bulloides* and dextral *N. pachyderma*. Species found in both assemblages are highly tolerant opportunists, suggesting species inhabiting the region during the climate instability of MIS 3 were able to survive rapidly changing environmental conditions. The assumption that large $\delta^{18}O$ shifts associated with rapid climate change were produced by 7° to 15°C SST shifts is now supported by census data SST reconstructions. However, wide temperature (5° to 25°C) tolerances of the dominant foraminiferal species and low species diversity contributed to the consistent overestimation of winter temperatures.

Faunal assemblage shifts also suggest the upper water column structure changed in association with stadials and interstadials. The upper water column appeared well mixed, with a shallow thermocline and SST of 7° to 8°C during the stadials of MIS 3, to become stratified and warmer (12° to 15°C) during interstadials. The large-magnitude SST changes associated with these rapid climate events resulted from changes in the California Current System and consequent advection of water masses into the basin. Evidence of upper water column conditions from $\delta^{18}O$ and planktonic faunal census data suggests North Pacific ocean-atmospheric circulation was oscillatory during MIS 3. These oscillations appear bimodal and little inertia appears to have been required to switch between warm and cold modes during this interval. This supports the conjecture that during MIS 3 the global climate system was located near a threshold between two modes of operation.

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