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Biomarker temperature estimates for modern and last glacial surface waters of the California Current system between 33° and 42°N

Heidi Doose
GEOMAR, Forschungszentrum für marine Geowissenschaften, Univertität Kiel, Germany

Fredrick G. Prahl
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis

Mitch W. Lyle
Center for the Geophysical Investigation of the Shallow Subsurface, Boise State University, Boise, Idaho

Abstract. Sea surface temperature (SST) estimates were made using data for C_{37-39} alkenones analyzed in modern and glacial-age intervals of sediment cores collected along an east-west (~42° N from 125° to 132° W) and a north-south (41°-33°N) transect of the California Current system (CCS). The prymnesiophyte biomarker results suggest that surface waters warmed significantly throughout this region since the last glacial maximum (LGM) but the magnitude of warming varied spatially. Stratigraphic profiles from four sediment cores along the north-south transect indicate the warming period was confined to the glacial/interglacial transition (15-10 ka), with SST reaching a maximum value at ~10 ka and maintaining a uniformly high value throughout the Holocene. Comparison of estimates derived from analysis of modern and LGM sediment intervals indicates the magnitude of the SST change was minimal for locations south of about 36°N (≤1°-2°C) and increased significantly (3°-5°C) north of this latitude. Using a simple heat balance model, we calculate from the latitudinal gradient in SST that southward flow in the California Current system during the LGM was about 60% of that measured today at 36°N. Our findings support the conclusion of others based on pollen data that coastal upwelling in the region of the northeast Pacific off northern California was significantly reduced or even completely shutdown during the LGM.

Introduction

Alkenones as paleotemperature indicators. Long-chain alkenones are recognized biosynthetic products of select phytoplankton genera belonging to the Class Prymnesiophyceae [*Marlowe et al.*, 1990]. Representative examples include the eurythermal coccolithophorid *Emiliana huxleyi*, the warm water coccolithophorid *Gephyrocapsa oceanica*, and the neritic noncalcareous *Isochrysis galbana* [*Volkman et al.*, 1995; *Marlowe et al.*, 1990].

Brassell et al. [1986] first linked alkenone unsaturation patterns to algal growth temperature and demonstrated use of stratigraphic measurements for the alkenone unsaturation index U^{k}_{37} in cores to assess variations in past sea surface temperature (SST). *Prahl and Wakeham* [1987] subsequently examined laboratory cultures of *E. huxleyi* isolated from the subarctic Pacific (strain 55a) and showed that the index $U^{k'}_{37}$ ($\equiv U^{k}_{37}$ when [37:4] = 0) is linearly well correlated with growth temperature over the range of 8°-25°C. The calibration equation established for strain 55a in batch cultures ($U^{k'}_{37} = 0.034 \times T + 0.039$) has been tested in the field and appears to provide realistic estimates of absolute surface water temperatures throughout much of the world ocean [*Brassell*, 1993, and references therein].

Nonetheless, recent studies show significant discrepancy can exist between water temperatures predicted by $U^{k'}_{37}$ and those actually measured in oceanic regions such as the eastern North Atlantic [*Conte et al.*, 1992] and, in particular, the Black Sea [*Freeman and Wakeham*, 1992]. Biomarker contribution from different or even multiple alkenone-producing algal sources perhaps best accounts for these exceptions. Further work with laboratory cultures has revealed a wide variety of $U^{k'}_{37}$- temperature calibrations for alkenone-producing prymnesiophytes including different strains of *E. huxleyi* [*Conte et al.*, 1994; *Prahl et al.*, 1995].

Alkenones occur as a series of C_{37}, C_{38}, and C_{39} methyl and ethyl ketones and are often accompanied by structurally related methyl and ethyl C_{36} alkenoates [*Marlowe et al.*, 1990]. Various indices besides U^{k}_{37} have now been devised to characterize quantitatively the biomarker composition of a given algae [e.g., *Prahl et al.*, 1988]. These include K37/K38 (a measure of alkenone chain length), K37:4/K37 (another measure of alkenone unsaturation), and ME/K37 (a measure of alkenoate to alkenone abundance). Examination of downcore data for these combined properties provides compelling evidence that the $U^{k'}_{37}$ - temperature calibration for *E. huxleyi* strain 55a isolated from the subarctic Pacific [*Prahl et al.*, 1988] would yield reliable estimates for SST and its long-term pattern of variation since the last glacial period in the California Current System (CCS) off Oregon and California.

Oceanography of the California Current system. The CCS represents the eastern boundary current of the North Pacific Gyre. It consists of the southward California Current,

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the northward California Undercurrent, the northward Davidson Current present nearshore above about 40°N in fall and winter, and the southward California Countercurrent below about 40°N [*Huyer*, 1983].The CCS connects the West Wind Drift in the north with the North Equatorial Current in the south [*Strub et al.*, 1990]. Seasonal changes in the intensity and specific orientation of the CCS are driven largely by the position of the North Pacific High which oscillates between about 28°N and 130°W in winter and between 38°N and 150°W in summer [*Huyer*, 1983]. Seasonal shifts in the position of the North Pacific High and differences in the intensity and direction of flow for individual currents within the CCS cause intra-annual variation in upwelling patterns along Oregon and California coastlines. The region of maximal wind stress toward the equator migrates northward from about 25°N in January to 36°N in July as expected from the seasonal movement of the North Pacific High [*Huyer*, 1983]. Northerly winds which drive coastal upwelling occur all year to the south of about 40°N and are strongest in July off northern California when the North Pacific High is positioned closest to a thermal low over western North America. Coastal upwelling north of about 40°N is episodic, on the other hand, and occurs most commonly during summer and early fall [*Hickey*, 1979]. A wind pattern change in late fall facilitates development of the Davidson Current, a nearshore northward current which acts to suppress coastal upwelling in this region.

In the present paper, we investigate the evolution of SST in the California Current system from the last glacial period to the present using alkenone unsaturation data ($U^{k'}_{37}$) obtained from analysis of a strategic set of stratigraphic sediment samples. Modern SST estimates derived from biomarker analyses are compared with average seasonal values reconstructed from the hydrographic data set for the world ocean compiled by *Levitus* [1982]. Results from this comparison are interpreted oceanographically given current understanding of seasonal production patterns for alkenones obtained from prior study of sediment trap time series for a transect along 42°N in the northeast Pacific [*Prahl et al.*, 1993]. Stratigraphic analysis of sediment cores shows a pattern of SST warming in the CCS from the last glacial period to the present confined to the time frame of 15-10 ka. The perceived magnitude of SST warming varies spatially, decreasing significantly from north to south. Our findings are placed in paleoceanographic perspective with published microfossil and pollen data available for this same region of northeast Pacific and interpreted in terms of the likely environmental factors that have acted to alter the character of the CCS from the last glacial maximum (LGM) to the present.

Materials and Method

Sample collection. Sediment intervals were selected from cores collected along an east-west (E-W) and a north-south (N-S) transect of the CCS (Figure 1 and Table 1). All cores situated along the E-W transect were collected as part of the National Science Foundation (NSF) sponsored Multitracers Project [see *Lyle et al.*, 1992]. Wet sediment subsamples from each of these cores were obtained from the core repository at Oregon State University (Corvallis, Oregon). All cores situated along the N-S transect were collected by the United States Geological Survey (USGS). Freeze-dried sediment subsamples from each of these cores were obtained from the USGS core repository (Menlo Park, California). Prior to subsampling, all cores had been stored under refrigerated conditions (4°C) in sealed D-tubes.

Sediment samples representing modern and LGM (18 ka) conditions were obtained from each core for organic geochemical analysis. In addition, a more detailed set of stratigraphic sediment samples was obtained at 20 cm intervals for the past ~30 kyr from cores V1-81-G15, F2-92-P3, and W8709A-13TC (Figure 1). Dates for each sediment interval were assigned based on chronology for respective cores developed previously by *Lyle et al.* [1992], *Ortiz* [1995], and *Gardner et al.* [1997]. Sediment chronologies were established using a combination of conventional ^{14}C measurements on bulk organic carbon, accelerator mass spectrometric (AMS) ^{14}C measurements on planktic foraminiferal carbonate and bulk organic carbon, bulk calcium carbonate stratigraphy, and/or stable oxygen isotope stratigraphy on planktonic foraminifera. Modern SST values for waters overlying each core site were extracted from the World Ocean Atlas

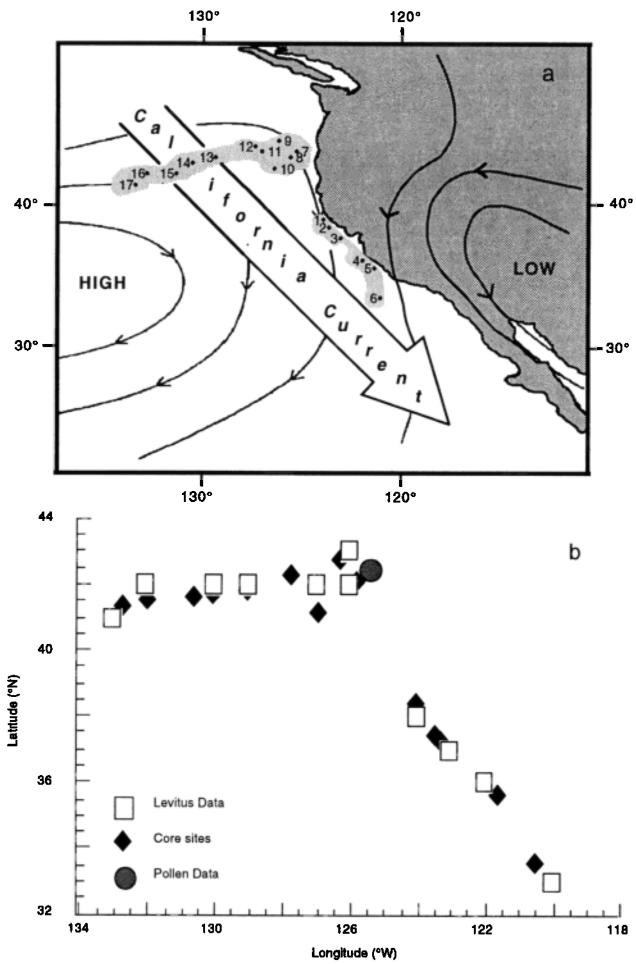

Figure 1. (a) Map showing locations where sediment cores examined in this study were collected. (b) Plot showing the correspondence between locations where sediment samples (solid diamonds) analyzed in this study and temperature data (open squares) for overlying surface waters [*Levitus*, 1982] were obtained. A core site is also indicated by the solid circle where pollen were obtained by *Sancetta et al.* [1992].

Table 1. Sea Surface Temperature Estimates From Alkenone Compositions Measured in Selected Stratigraphic Intervals of Sediment Cores From the California Current System Between 33°-42° N Latitude and 125°-132°W Longitude.

Station Number	Core	Latitude	Longitude	Water Depth, m	Core Depth, cm	Age, ka	UK'37	SST, °C
			North-to-South Transect					
1	L13-81-G138	38°24.8'N	123°58.2'W	2531	2.0	0.0	0.479	13 0
					19 0	3.0	0.448	12 0
					149.0	18.0	0 305	7.8
2	F8-90-G25	37°27.0'N	123°19.8'W	1720	4.0	6 0	0.468	12.6
					109 0	12.0	0 381	10.1
3	F8-90-G21	37°13.2'N	123°14.4'W	1605	2.0	6 0	0.475	12.8
					141 0	15 0	0 325	8.4
					162.0	17 0	0.339	8.8
4	F2-92-P3	35°37.4'N	121°36.3'W	803	3.0	1.0	0.522	14 2
					31.0	4.0	0.498	13 5
					61.0	6 0	0.504	13.7
					91.0	9.0	0 484	13.1
					101.0	10.0	0.491	13.3
					131.0	11.0	0 485	13.1
					149.0	12.0	0.454	12.2
					171.0	14.0	0 486	13.2
					191.0	14.0	0.442	11.8
					219 0	15.0	0.405	10.8
					291.0	19 0	0 461	12.4
5	F2-92-P34	35°01 9'N	121°13 5'W	610	1.0	0.0	0.520	14.1
					100.0	10 0	0.516	14.0
					200 0	19 0	0.385	10 2
6	V1-81-G15	33°36 0'N	120°25 2'W	1430	3 0	0 0	0.539	14 7
					25.0	3.0	0.530	14 4
					45.0	6.0	0.538	14.7
					65.0	10.0	0.542	14.8
					70.0	10.0	0.552	15 1
					75.0	11.0	0.531	14 5
					80.0	12.0	0.518	14.1
					85.0	13.0	0.504	13.7
					90 0	14.0	0 490	13.3
					95.0	14.0	0.482	13.0
					120.0	19.0	0.487	13.2
			East-to-West Transect					
7	W8709A-13TC	42°07.2'N	125°45.0'W	2741	0.5	0 0	0.416	11 1
					10.0	5.3	0.414	11 0
					30.0	6 2	0.414	11.0
					48.0	7.1	0.410	10.9
					70.0	8.2	0.394	10.4
					90.0	9.1	0.392	10.4
					110.0	10.1	0.438	11.7
					130.0	11.1	0.410	10.9
					149.0	12.0	0.338	8.8
					170.0	13.0	0.322	8.3
					190.0	14.0	0.312	8.0
					210.0	15.0	0.288	7.3
7	W8709A-13PC	42°07.0'N	125°45.0'W	2712	170.0	13.0	0.285	7.2
					189.5	14.0	0.290	7.4
					189.5	14.0	0.285	7.2
					209.5	14.9	0.269	6.8
					229.5	15.9	0.258	6.4
					248.5	16.8	0.261	6.5
					289.5	18.8	0.252	6.3
					310.0	19 8	0.263	6.6
					329.5	20 8	0.224	5.4
					349.5	21.7	0.250	6.2
					369.5	22.7	0.231	5.6
					389.5	23.7	0.208	5.0
8	W8709A-09BC	42°04.8'N	125°49 3'W	2814	0.0	0.0	0.394	10 4
9	W8809A-53GC	42°45.0'N	126°15 5'W	2408	1.0	0.0	0.446	12.0
					168.0	18.0	0.288	7.3
10	W8809A-21GC	41°08.4'N	126°54.4'W	2799	1.0	0 0	0.382	10.1
					140 0	18.0	0.325	8.4
11	W8709A-06BC	42°15 0'N	127°38.3'W	2914	0.0	0.0	0.454	12.2
12	W8709A-8TC*	42°32.5'N	127°40.7'W	3111	0.5	0.0	0 427	11.4
					2.5	0.2	0.438	11.7
					4.5	0.4	0 435	11.6
					23.5	2.1	0.484	13.1
					26.0	2.3	0.414	11.0
					47.5	4.5	0.421	11.2
					65.5	6 4	0.427	11.4
					67.5	6.6	0 427	11.4
					88.5	8.9	0.428	11 4

Table 1. (continued)

Station number	Core	Latitude	Longitude	Water Depth (m)	Core depth (cm)	Age (ka)	UK'37	SST (°C)
12	W8709A-8TC*	42°32.5'N	127°40.7'W	3111	89.5	9.0	0.477	12.9
					97.5	9.9	0.448	12.0
					107.5	10.9	0.417	11.1
					117.5	12.0	0.364	9.6
					127.5	13.1	0.391	10.4
					128.5	13.2	0.369	9.7
					134.5	13.9	0.308	7.9
					137.5	14.2	0.309	7.9
					140.5	14.6	0.317	8.2
					141.5	14.7	0.331	8.6
					144.5	15.0	0.339	8.8
					146.5	15.2	0.328	8.5
					149.5	15.5	0.326	8.4
					152.5	15.8	0.337	8.8
					157.0	16.3	0.308	7.9
					163.5	17.0	0.323	8.4
					166.5	17.4	0.333	8.6
					175.0	18.1	0.315	8.1
					183.5	19.0	0.319	8.2
					185.5	19.2	0.301	7.7
12	W8709A-8PC*	42°32.5'N	127°40.7'W	3111	159.5	16.6	0.271	6.8
					178.5	18.5	0.323	8.4
					199.5	20.5	0.249	6.2
					219.5	22.2	0.265	6.6
					239.5	23.7	0.226	5.5
					259.5	25.1	0.227	5.5
					259.5	25.1	0.235	5.8
					279.5	26.5	0.294	7.5
					299.5	28.0	0.249	6.2
					319.5	29.4	0.311	8.0
13	W8809A-29GC	41°48.0'N	129°00.2'W	3288	1.0	0.0	0.422	11.3
					145.0	18.0	0.262	6.6
14	W8809A-31GC	41°40.8'N	130°00.4'W	3136	1.0	0.0	0.401	10.6
					6.5	18.0	0.401	10.6
15	W8909A-57GC	41°34.8'N	130°37.0'W	3330	1.0	0.0	0.456	12.3
					18.0	18.0	0.293	7.5
					46.0	38.0	0.305	7.8
16	W8709A-01BC	41°32.4'N	131°57.6'W	3680	0.0	0.0	0.452	12.2
					21.0	17.0	0.319	8.2
17	W8909A-48GC	41°19.8'N	132°40.0'W	3670	2.0	1.0	0.367	9.6
					16.0	18.0	0.273	6.9
					17.0	18.0	0.281	7.1

* Data extracted from *Prahl et al.* [1995]

[*Levitus*, 1982]. Figure 1b illustrates the spatial correspondence between the position for actual modern SST measurements and core sites used for estimation of modern and LGM SST.

Analytical methods. Total lipids were extracted ultrasonically from sediment (~3 g dry) using a 1:3 solvent mixture of toluene in methanol (15 ml, 3x). A fraction containing unsaturated C_{37-39} methyl and ethyl ketones and unsaturated methyl and ethyl C_{36} alkenoates was then isolated from the total lipid extract by column chromatography on silicagel. All fractions were analyzed quantitatively by an internal standard method using an HP5890A gas chromatograph (GC) equipped with on-column injection, a fused silica capillary column (30 m x 0.25 mm ID DB-1, J&W Scientific) and flame ionization detection (310°C). GC separations were accomplished using hydrogen as carrier gas (0.35 kg/cm^2 constant head pressure) and temperature programing (100°-300°C at 5°C/min). Typical chromatograms from this analysis are reported by *Prahl et al.* [1995]. Further details of the chemical workup procedure and instrumental method of alkenone/alkenoate analysis are discussed elsewhere [*Prahl et al.*, 1989, 1993].

Results and Discussion

Biomarker assessment of surface water temperature. Recent laboratory studies have shown significant differences in the response of alkenone unsaturation patterns ($U^{k'}_{37}$) to growth temperature between cultured strains of *E. huxleyi* isolated from various geographic regions of the world ocean [*Conte et al.*, 1994; *Prahl et al.*, 1995]. Work with cultures [*Volkman et al.*, 1995] also indicates that the temperature response of $U^{k'}_{37}$ in a related prymnesiophyte, *Gephyrocapsa oceanica*, differs significantly from that first reported for strain 55a of *E. huxleyi* (i.e., $U^{k'}_{37} = 0.034 \times T + 0.039$ [*Prahl et al.*, 1988]). Although quantitative details of $U^{k'}_{37}$-T relationships vary dramatically between alkenone-producing prymnesiophytes, values for this parameter increase in direct proportion to growth temperature in all algae capable of this biosynthesis.

C_{37-39} alkenones are ubiquitous in sediments from our study area in the northeast Pacific Ocean. $U^{k'}_{37}$ values measured in the complete set of sediment samples range from 0.208 to 0.552 (Table 1). This range corresponds to water temperature spanning from 5° to 15°C if interpreted using the calibration

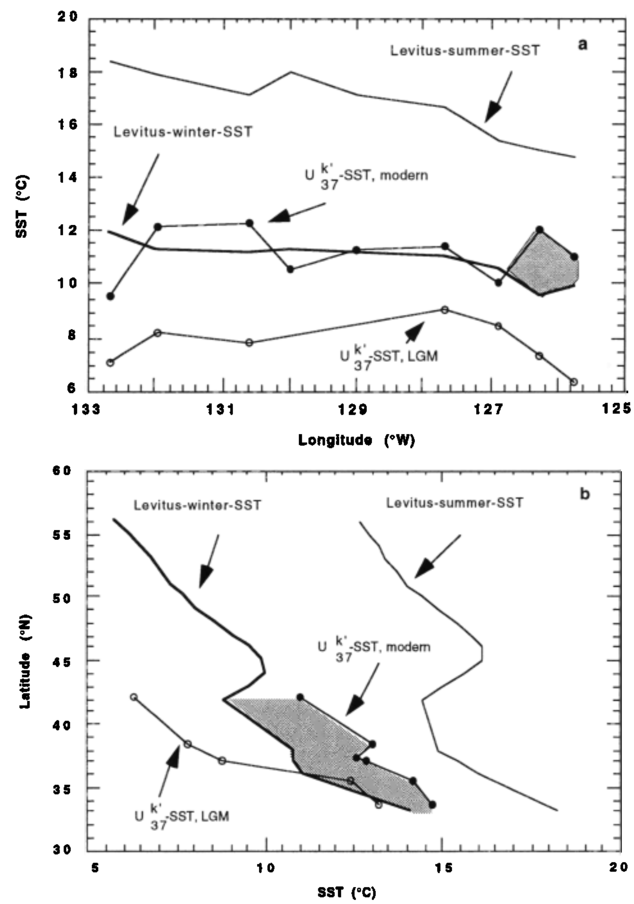

Figure 2. $U^{k'}_{37}$-derived estimates for sea surface temperature (SST) in modern and LGM (18 ka) waters of the California Current system (CCS). The biomarker estimates are compared with mean winter and summer SST [*Levitus*, 1982] measured in overlying waters above corresponding core sites along the (a) east-west and (b) north-south transects of the CCS.

equation defined for *E. huxleyi* strain 55a. Prior study of alkenones in sediment trap particles [*Prahl et al.*, 1993] and sediments [*Prahl et al.*, 1995] from the northeast Pacific suggests the calibration for 55a is an appropriate choice, yielding reasonable estimates of average growth temperature for alkenone-producers in surface waters of this study region. In fact, for reasons yet unknown, the calibration for this strain of *E. huxleyi* isolated from the subarctic Pacific appears well suited for assessment of surface water temperatures throughout much of the world ocean [*Brassell*, 1993; *Rosell-Mele et al.*, 1995; *Sikes and Volkman*, 1993].

Spatial trend for modern SST estimates. Figure 2 compares modern SST estimates derived from $U^{k'}_{37}$ measured in surface sediment using the temperature calibration for *E. huxleyi* strain 55a with average summer and winter SST physically determined for this region [*Levitus*, 1982]. Notably, average winter and summer SST bracket the biomarker estimates, reinforcing their credibility. A systematic spatial trend also stands out in this comparison. Estimates along the N-S transect consistently plot ~2°C warmer than average winter SST observed near the continental margin, whereas estimates made seaward of the continental margin along the E-W transect virtually overlay average winter SST observed farther offshore.

We submit that this trend is physically real and can be explained in view of recent observations made with sediment traps deployed in time series along the E-W transect [*Prahl et al.*, 1993]. Sediments deposited remote from the continental margin receive a dominant alkenone flux from the water column at the onset of the spring transition, the period of the year when the ocean shifts modes from that of deep winter mixing to summer stratification. Sediments deposited near the continental margin receive more uniform alkenone flux from the water column throughout the year. Consequently, $U^{k'}_{37}$ values measured in underlying sediments, which represent a weighted average of alkenone contribution from the water column flux throughout the year, are biased seasonally for cold winter SST in the offshore. Average $U^{k'}_{37}$ measured in nearshore sediments, on the other hand, are less seasonally biased and reflect somewhat warmer, mean annual SST.

Comparison of modern and LGM SST estimates. Table 1 summarizes SST estimates made for the complete set of $U^{k'}_{37}$ data from this study using the calibration equation for *E. huxleyi* strain 55a. Modern and LGM SST estimates along the E-W and N-S transects are compared in Figure 2. At all sites, modern SST estimates are warmer than those for the LGM, but the magnitude of SST difference varies from the northern to the southern part of the survey. Notably, LGM SST estimates are typically below modern winter SST from *Levitus* [1982]. atlas. Provided that the temperature calibration for $U^{k'}_{37}$ is maintained, explanation for this feature requires average LGM conditions to be significantly cooler. It is possible that a change in the season of maximum alkenone production occurred and thereby influenced the apparent trend. However, it seems unlikely that the observed spatial pattern for LGM SST estimates could be explained exclusively by this biological oceanographic process.

In the north, there is a 3°-5°C SST difference between the LGM and the modern ocean (Figure 2). This temperature difference is consistently found along the E-W transect at 42°N, and the magnitude of the change is comparable to independent SST estimates based on radiolarian faunal abundances in the same sediments [*Prahl et al.*, 1995]. Such large temperature differences are evident between LGM and modern SST estimates north of about 36°N. South of this latitude the difference narrows abruptly to 1°-2°C. On the basis of the alkenone temperatures, therefore, average LGM SST were only slightly cooler than modern SST south of central California.

Herbert et al. [1995] analyzed alkenones at Site 893 in the Santa Barbara Basin (34°17.3'N, 120° 02.2'W) and established for this region of the California Borderlands a SST stratigraphy for the LGM to the present. Findings from our study for the region south of 36°N generally echo their results. The difference in SST between LGM and modern found at Site 893 was only 1°-2 °C, while the last major cooling occurred at 30-40 ka. At 30 ka, for example, the SST difference from modern is ~4°C at Site 893. Since the LGM, then, all alkenone measurements available so far from south of 36°N produce a consistent pattern of minimal temperature change.

In contrast, *Kennett and Venz* [1995] propose for this region of the northeast Pacific a temperature change of 7°-8°C from the LGM to the modern ocean, from ~8°C to 15°C. Their estimates are based on coiling ratios of the planktonic foraminifera *N. pachyderma.* The coiling ratio switched from >90% sinistral in LGM sediments to >90% dextral in modern sediments. By comparison to modern foraminiferal and SST distributions, they argue that such a sinistral dominance would only be found in waters around 7°-8°C. Nevertheless, left-coiling *N. pachyderma* are very abundant in recently upwelled waters in the modern northeast Pacific [*Ortiz and Mix,* 1992], so the change may reflect changes in upwelling pattern, rather than temperature. As an example, *Ortiz and Mix* [1992] measured an annual average coiling ratio of 64% sinistral in sediment traps deployed 121 km from the coast of southern Oregon in waters with an annual temperature range of 10°-17°C and seasonal coiling ratios of 95% sinistral during the upwelling season when SST is about 12°C. The *Kennett and Venz* [1995] statistical observation could therefore also be explained by net higher upwelling in the California Borderlands region at the last glacial maximum or some other ecological complication.

The discrepancy between the two SST estimates is extremely important to understand because as discussed below, the paleoceanographic implications are significant. We have confidence in the alkenone estimates not only because of our own work and the good agreement between alkenone and other faunal estimates of SST, but also because very high resolution alkenone studies in the Santa Barbara Basin failed to reveal any strong annual or interannual bias from modern SST measurements [*Kennedy and Brassell,* 1992].

Time series of alkenone SST. $U^{k'}_{37}$ was analyzed stratigraphically in four cores from various parts of the study area (W8709A-8TC and PC, W8709A-13TC and PC, F2-92-P3 and V1-81-G15; Figure 1). Figure 3 displays p@ files for estimated water temperatures versus sediment age observed in each of these cores. At the nearshore (W8709A-13TC/PC) and at the midway (W8709A-8TC/PC) sites, $\delta^{18}O$ data from *Lyle et al.* [1992] were compared with our stratigraphic records for $U^{k'}_{37}$-predicted SST (left and middle panels in Figure 3). The $\delta^{18}O$ maximum defining the LGM is not coincident with our lowest SST estimates. Instead, the lowest temperatures experienced at 42°N in the last 30 kyr (~5.5°C) are found at about 23-25 ka. From about 20 to 15 ka, temperature estimates are quite uniform (~6.5°C) but slightly warmer. The processes which control this trend are not yet clear, and longer records must be analyzed to determine if a consistent phase relationship exists with orbital forcing parameters. The records are consistent, however, with a relatively strong response in phase with Earth's tilt cycle, as was observed at Site 893 by *Herbert et al.* [1995]. Such a response would mean that SST along the California margin is strongly driven by high-latitude insolation.

The observed warming between the LGM and modern sediment intervals occurs consistently within the time frame of the glacial-interglacial transition (15-10 ka) from 33°N to 42°N along the California margin. There is no evidence for structure in the timing of deglaciation. A slight SST maximum at about 10 ka is a consistent feature of the $U^{k'}_{37}$ time series. After that time, estimated SST variability is low throughout the Holocene.

Paleoceanographic implications for the California Current system. The latitudinal gradient of SST estimates for the California margin changes dramatically from LGM to the present. At 18 ka, the SST gradient was about twice that of today (i.e., ~0.8 °C per degree of latitude then versus ~0.4° per degree of latitude now). A simple heat balance model can be used to show that the larger LGM SST gradient implies significantly smaller flow for the CCS than modern conditions.

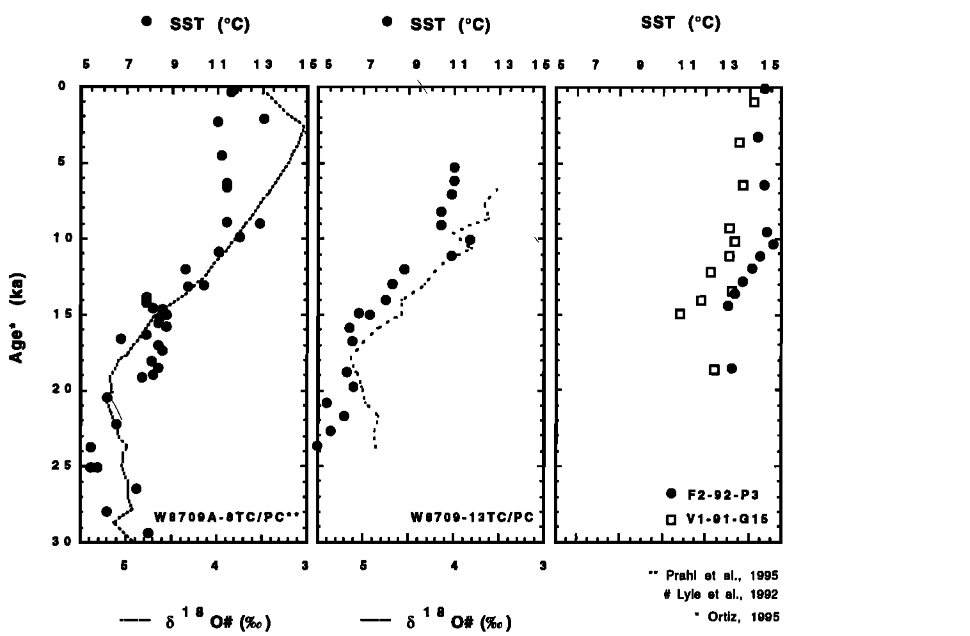

Figure 3. Stratigraphic profiles of sea surface temperature estimates in dated cores collected at four sites (W8709A-8TC/PC, W8709A-13TC/PC, F2-92-P3, and V1-91-G15) beneath the California Current system off the west coast of Oregon and California. SST was estimated from $U^{k'}_{37}$ measurements using the calibration equation: $U^{k'}_{37} = 0.034 \times T + 0.039$ [*Prahl et al.,* 1988]. All data shown for W8709A-8TC/PC are those previously published by *Prahl et al.* [1995].

The heat balance of the California Current can be expressed by the following equation, assuming that downward and east-west exchanges of heat are insignificant:

$$T_{in} x J_{in} x C_p x \rho_w + T_{up} x J_{up} x C_p x \rho_w + I = T_{out} x J_{out} x C_p x \rho_w \quad (1)$$

In this equation, T_{in} and J_{in} are the temperature (°C) and flow (in sverdrups (Sv), 10^6 m^3/s) of water entering the California Current in the northern part; T_{out} and J_{out} are the temperature and flow of water leaving the California Current in the south; T_{up} and J_{up} are the temperature and flow of waters upwelling into the California Current system; I is the heat added by insolation; and C_p and ρ_w are the heat capacity and density, respectively, of the water.

Equation (1) can be solved for mass transport in the south (J_{out}), which should be the average total horizontal advection in the California Current, as

$$J_{out} = (T_{in} x J_{in} + T_{up} x J_{up} + I')/T_{out} \quad (2)$$

where I' is I/C_p x ρ_w. This equation still has several variables which must be evaluated before it can be applied to LGM conditions. Insolation heating for modern conditions can be calculated by substituting known terms for advection. We can assume that insolation heating did not change much at the LGM and that this variable is essentially constant. While this interpretation is overly simplified, it is important to remember that insolation reaching the upper atmosphere at 18 ka was only a few percent different from modern [*Berger*, 1978]. Therefore changes in cloudiness in the California margin would make the only major difference in this term. If cloudiness has not changed significantly, LGM insolation can be approximated by its modern value. Nonetheless, it is also important to recognize that a reduction of insolation would reduce the SST gradient within the CCS while only a large increase in insolation would increase the SST gradient as much as we have observed.

To further simplify the equation, the different water fluxes can be linked by a mass balance:

$$J_{out} = J_{in} + J_{up} \quad (3)$$

Southward flux of the modern California Current (J_{out}) is approximately 10 Sv [*Hickey*, 1979]. The upwelling term (T_{up} x J_{up}) can be estimated from *Huyer* [1983]. Offshore Ekman transport between Point Conception (35°N) and Cape Blanco (43°N) is between 50 and 100 metric t/s/100m of shoreline. Since there is about 1000 km between these two coastal features, this translates into an average annual upwelling between 0.5 and 1 Sv. Assuming 1 Sv of upwelling with temperature (T_{up}) 4°C colder than surface waters and given modern SST estimates from $U^{k'}_{37}$ measurements at the north and south (11°C and 14.5°C, respectively), insolation (I') can then be fixed at 39 Sv-°C.

If at the LGM (1) upwelling was unchanged, (2) upwelled waters were also ~4°C colder than surface waters, and (3) SST estimated by alkenones was again representative of surface conditions, then transport of the California current (J_{out}) is calculated as 5.8 Sv, or ~60% of modern flow. If coastal upwelling had ceased completely between 35° and 43°N at the LGM, the calculated transport would be slightly higher (6.5 Sv), or ~65% of modern flow. Cessation of upwelling in this region has been suggested by the absense of redwood pollen from glacial intervals of W8709A-13TC and PC [*Sancetta et al.*, 1992].

Clearly, the larger LGM temperature gradient implies that southward flow must have been weaker than under modern conditions. If further work substantiates the SST gradients documented in our study, flow in the California Current at the LGM between 42° and 35° N was probably about 60% of modern flow. Such reduced flow of the California Current within this latitudinal band probably resulted from southward expansion of the subarctic Alaskan gyre and transition region into the subtropical North Pacific Gyre [*Moore et al.*, 1981]. Such an expansion would imply a weaker or more southerly subtropical North Pacific High pressure cell and lower coastal upwelling in this latitudinal band. Such changes in climatic and physical oceanographic conditions have been proposed by other studies [Cooperative Holocene Mapping Project (*COHMAP*), 1988; *Lyle et al.*, 1992].

The weaker flow in the northern region of the modern California Current does not imply, however, that flow within the southern California Current along Baja California was also weaker at 18 ka. In fact, data at the mouth of the Gulf of California imply that the California Current at the LGM extended farther south and entered into the Gulf of California [*Molina Cruz, 1988*]. The contrast between the behavior of the northern and southern parts of the CCS is not unexpected and results from different behavior of the northern and southern parts of the temperate zone during the change from a glacial to an interglacial climate regime. Further work along Baja California must be performed, however, to better understand and quantify the oceanographic processes.

Conclusions

1. The $U^{k'}_{37}$- T calibration established for strain 55a of *E. huxleyi* isolated from the subarctic Pacific Ocean provides reliable estimates of past surface water temperature in the California Current system (CCS).

2. Modern water temperature estimates for sites most remote from the continental margin are equivalent to mean winter SST. Modern water temperature estimates for sites near the continental margin are consistently 1°-3°C warmer than mean winter SST. This spatial trend is attributed to upwelling that occurs seasonally or year around in the CCS between 33° and 42°N.

3. Surface water temperatures in the glacial-age CCS between 33° and 42°N were colder than those today. The magnitude of the difference between modern and glacial-age estimates for surface water temperature varied systematically from a minimum of 1°-2°C south of about 36°N to ~5°C north of this latitude.

4. Our biomarker observations imply that southward transport of water in the CCS was reduced as much as 60% during the LGM. Furthermore, they support the conclusion drawn from pollen data [*Sancetta et al.*, 1992] that coastal upwelling north of about 36°N in the CCS was weaker in the LGM than at present and was perhaps even nonexistent. This process intensified during the period of glacial-interglacial transition (15-10 ka).

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H. Doose, GEOMAR, Forschungszentrum für marine Geowissenschaften, Wischofstraβe 1-4, 24148 Kiel, Germany. (e-mail: hdoose@geomar.de)

M.W. Lyle, Center for the Geophysical Investigation of the Shallow Subsurface, Boise State University, Boise, ID 83725. (e-mail: mitch@rowena.idbsu.edu)

F.G. Prahl, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331. (e-mail: fprahl@oce.orst.edu)

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