The California Current of the last glacial maximum: Reconstruction at 42°N based on multiple proxies

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Abstract: Multiple paleoceanographic proxies in a zonal transect across the California Current near 42°N record modern and last glacial maximum (LGM) thermal and nutrient gradients. The offshore thermal gradient, derived from foraminiferal species assemblages and oxygen isotope data, was similar at the LGM to that at present (warmer offshore), but average temperatures were 3.3° \( \pm 1.5 \) C colder. Observed gradients require that the sites remained under the southward flow of the California Current, and thus that the polar front remained north of 42°N during the LGM. Carbon isotopic and foraminiferal flux data suggest enhanced nutrients and productivity of foraminifera in the northern California Current up to 650 km offshore. In contrast, marine organic carbon and coastal diatom burial rates decreased during the LGM. These seemingly contradictory results are reconciled by model simulations of the LGM wind-field, which suggest that wind stress curl at 42°N (and thus open-ocean upwelling) increased, while offshore Ekman transport (and thus coastal upwelling) decreased during the last ice age. The ecosystem of the northern California Current during the LGM approximated that of the modern Gulf of Alaska. Cooling and production in this region was thus driven by stronger open-ocean upwelling and/or southward flow of high-latitude water masses, rather than by coastal upwelling.

Introduction

We report here on conditions in the northern California Current during the last glacial maximum (LGM). Previous studies suggest that NE Pacific surface waters cooled by 2°-4°C [Moore, 1973; Moore et al. 1980] and that export production decreased relative to present values [Lyle et al. 1992; Sancetta [Moore, 1973; Moore et al. 1980] and that export production decreased relative to present values [Lyle et al. 1992; Sancetta et al. 1992]. These past studies were limited to a few cores at different latitudes, which precludes resolution of water mass flows. To resolve regional currents, we focus on zonal temperature and nutrient structures at 42°N in a transect of 10 cores that span the California Current from 125°W to 134°W. To evaluate causes of oceanographic change, we compare geologic data with local wind forcing simulated with a regional climate model.

Our transect, located between Cape Blanco and Cape Mendocino, is sensitive to southward translation of the polar front zone (the boundary between the subarctic and subtropical gyres) because it is near the southern boundary of the transition zone between these gyre systems. Today, year-round flow is southward (Figure 1) and near-coastal upwelling is strong in summer. By reconstructing the LGM zonal thermal gradient here we infer direction in the surface water circulation and thus put limits on polar front movements.

Had the LGM polar front moved south of these sites, flow across the transect would have been northward, similar to the Alaskan Stream off British Columbia today. This would be indicated by warmer, more nutrient-depleted water near the coast than offshore. If the LGM polar front stayed to the north, our sites would have remained under a southward flowing California Current, with colder nutrient-enriched water near the coast and warmer, more nutrient-depleted waters offshore.

Methods

Foraminiferal Faunas: Temperature and Productivity Estimates

We identified foraminiferal species percentages in the >150-\( \mu \)m size class using standard CLIMAP taxonomic categories [Parker, 1962; Be, 1977] with one exception. In this study, we do not recognize the "Neogloboquadrina pachyderma - neogloboquadrina dutertrei (P-D) intergrade" category of Kipp [1976].

We compare modern foraminiferal faunas from sediment traps and plankton tows with local fossil assemblages obtained from well-preserved LGM sediments (Table 1). Core top faunas in this area are highly dissolved and thus unusable for our study [Karlin et al. 1992; Zahn et al. 1991b; Lyle et al. 1992].
Figure 1. Locations of the sediment cores (solid circles) and sediment trap moorings (solid circles surrounded by circles) across the California Current near 42°N. Contours are the climatic average dynamic height field relative to 500 m in units of geopotential (m² s⁻²). Geopotential is a measure of the geostrophic flow during (a) August, September, and October and (b) February, March, and April, using data from Levitus [1982]. Closer contours denote faster currents; arrows show the direction of flow.

Table 1. Multitracers Core and Trap Locations

<table>
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<tr>
<th>Name</th>
<th>Age Control a</th>
<th>Latitude, °N</th>
<th>Longitude, °W</th>
<th>Depth, m</th>
<th>Length, cm</th>
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<td>Gyre trap</td>
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<td>1000</td>
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</table>

aThree methods of age control are used: Type 1 is carbonate stratigraphy, type 2 is conventional ¹⁴C dating of bulk organic matter [from Spigai, 1971], and type 3 is AMS ¹⁴C on planktic or benthic foraminifera.
Foraminiferal sediment trap fluxes are from Ortiz and Mix, [1992], but were modified by grouping P-D intergrade with Neogloboquadrina dutertrei.

Paleotemperature estimates use a version of the modern analog method tested on both core top and sediment trap faunas [Ortiz and Mix, this issue]. This method yields unbiased sea surface temperature (SST) estimates with an RMS error of 1.5°C for the core top data set. Additional checks include (1) radiolarian paleotemperature estimates [Sabin and Pisias, 1996], and (2) δ18O measurements of G. bulloides.

We infer LGM nutrient content and foraminiferal productivity from (1) δ13C gradients of G. bulloides across the transect and (2) shell accumulation rates of the heterotrophic planktonic foraminifera. Modern shell accumulation rates are from sediment trap fluxes, subject to little or no dissolution. LGM faunas are well preserved, but possible losses due to partial dissolution imply that preserved accumulation rates are minimum estimates for original shell fluxes. We assume a relationship between water column nutrient content and shell fluxes because nutrients control the food supply of heterotrophic foraminifera [Ortiz 1995; Ortiz et al. 1995; Ortiz and Mix, 1992]. Given a life span of about 1 month [Hemleben et al. 1988], foraminifera like other zooplankton can respond to changes in prey abundance related to upwelling events of several weeks duration, in addition to advective changes on longer timescales [Barnard, 1994].

Age Models

Age models are needed both for synoptic sampling of the LGM and for calculating sediment accumulation rates. Core locations are given in Table 1. Stratigraphic control includes calcium carbonate percentages, oxygen isotope stratigraphy, and radiocarbon dating. The LGM horizon, defined here as between calendar-corrected radiocarbon ages of 16-22 ka, is associated with high %CaCO3 in cores east of 129°W (Figure 2) [Lyle et al. 1992]. Further west, the carbonate high is broader, and the LGM horizon is chosen near the younger end of the carbonate high. Carbonate percentage data are in Table 2.

Radiocarbon dates on foraminifera come from Lyle et al. [1992], Gardner et al. [this issue], and the present study (Table 3). Dates from consecutive 2-5 cm intervals that were not statistically independent were averaged. Reservoir corrections, needed to adjust for the apparent 14C age of the water in which the foraminifera lived, assume that benthic foraminifera calcified in North Pacific deep waters with Δ14C = -250‰ [Ostlund et al. 1987], as defined on the Δ14C scale of Stuiver and Polach [1977]. The benthic reservoir correction is thus 2380 years, using the "Godwin" '4C half-life of 5730 years [Faure, 1977]. Subtracting the average 14C age difference between benthic and planktonic foraminifera in the same samples from the assumed benthic reservoir correction, we find a planktonic reservoir correction of 718 years. This estimate is virtually

![Figure 2. Percent carbonate stratigraphies for the 10 cores in the transect, ordered by distance from the coast: 6706-2 is closest to the coast, while W8909a-48GC is farthest offshore. Solid squares mark the last glacial maximum (LGM) samples identified by carbonate stratigraphy and AMS-14C dating. Some carbonate data for 6706-2 are from Spigai [1971]. Carbonate data for W8709a-13PC, 13TC, W8709a-8PC, TC, and W8709a-1BC from Lyle et al. [1992].](image-url)
identical to that of Zahn et al. [1991a]. The benthic-planktonic age comparison in five samples of up to 25,000 ¹⁴C years suggests that the average reservoir age of the surface water was roughly constant over that time interval. We thus subtracted 718 years from each of the planktonic foraminiferal dates, and 2380 years from each of the benthic foraminiferal dates, for reservoir corrections. Reservoir corrections on bulk organic carbon dates are calculated to align their ages with those of the reservoir-corrected calcite dates. This empirical correction (4300 years) is larger than any reasonable open-ocean reservoir age. It implies that some older reworked material is present as part of the bulk organic carbon. The conclusions of this study would not change if the organic carbon dates were excluded.

The reservoir-corrected benthic and planktonic ages of >5000 ¹⁴C years were converted to calendar age (Table 3) using the nonlinear relationship of Bard et al. [1992]:

\[
\text{calendar age} = -5.85 \times 10^{-4} \times (\text{conventional } \Delta ^{14}C \text{ age})^2 \\
+ 1.39 \times (\text{conventional } \Delta ^{14}C \text{ age}) - 1807. \quad (1)
\]

The term "conventional ¹⁴C age" refers to ¹⁴C ages in radiocarbon years which have been reservoir corrected. Data used to construct the non-linear relationship of Bard et al. [1992] are published by Bard et al. [1993]. Bard et al. [1992] also present a linear relationship for use with ¹⁴C dates from 9 to 18 ka. Differences between these two relationships (linear minus nonlinear) range from 5 to 360 years. The differences between these two equations are thus comparable to the 2σ errors of our dates. Likewise, calendar correction factors from equation (1) for ages of <5000 ¹⁴C years are close to the precision of the AMS ¹⁴C dates. We did not attempt any correction factors for these relatively young dates. E. Bard (personal communication, 1996) considers equation (1) appropriate for samples between ¹⁴C ages of 10,000 and 22,000 years, and thus well constrained for calendar correction of our LGM samples.

### Table 2. Carbonate Stratigraphies for the Multitracer Cores

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<tr>
<th>Depth, cm</th>
<th>CaCO₃</th>
<th>Depth, cm</th>
<th>CaCO₃</th>
<th>Depth, cm</th>
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*Core top occurs at approximately 135 cm depth due to double coring.*

### Stable Isotopic Measurements

Oxygen (δ¹⁸O) and carbon (δ¹³C) stable isotopes were measured at Oregon State University using a Finnigan MAT-251 stable isotope mass spectrometer, equipped with an Autoprep Systems automated carbonate preparation device. Each sample consisted of 12 G. bulloides shells (300- to 355-µm size) collected from the LGM horizon in 10 sediment cores. Isotopic data use the standard isotopic delta notation (δ), in per mil (‰) relative to the Pee Dee belemnite (PDB) scale. Calibration to PDB was done through the NBS-19 and NBS-20 standards of the National Institute of Standards and Technology. External precision estimates for δ¹⁸O and δ¹³C, based on replicate analyses of local calcite standards, are ±0.08 and ±0.04‰, respectively.

Regional salinity (S) and the oxygen isotopic composition of water (δ¹⁸Ow) are positively correlated [Craig and Gordon, 1965]. Because δ¹⁸Ow is a function of both temperature (T) and δ¹⁸Ow, lines of constant δ¹⁸Ow plotted in T-S space approximate lines of constant density. This relationship holds over small spatial scales where it is safe to assume that the regional salinity - δ¹⁸Ow slope and intercept are constant. We thus use the slope of δ¹⁸Ow along the 42°N transect as a crude measure of the LGM density gradient. This gradient yields an estimate of surface water flow direction and magnitude, assuming geostrophy.
We estimate the oxygen isotopic composition of calcite in equilibrium with the water column ($\delta^{18}O_w$) using $T$ and $\delta^{18}O_{w}$ as inputs to the paleotemperature equation of Epstein et al. [1953]. For modern conditions we use SST and surface salinity to estimate the oxygen isotopic composition of calcite in equilibrium with the water column ($\delta^{18}O_w$) using $T$ and $\delta^{18}O_{w}$ as inputs to the paleotemperature equation of Epstein et al. [1953].

$$\delta^{18}O_w = 0.405(\text{salinity}) - 14.01 \text{‰}.$$  \hfill (2)

To estimate the relative magnitude of the LGM SST and surface salinity changes recorded in $\delta^{18}O_w$, we assume (1) an LGM ice volume $\delta^{18}O$ effect of +1.3‰ relative to present values and (2) the same as at present, and (3) a constant depth habitat for $G. bulloides$ ($0 - 30$ m in these sites at present [Ortiz et al. 1995]). The third assumption is the weakest. In the Gulf of Alaska, $G. bulloides$ resides between 100 and 150 m [Miles, 1973; Zahn et al. 1991a]. This depth range is within the main pycnocline, below the base of the mixed layer and above the North Pacific halocline. According to Zahn et al. [1991a], this subsurface habitat makes the $\delta^{18}O$ of late holocene $G. bulloides$ up to 1‰ enriched relative to seasonally weighted surface water $\delta^{18}O_w$ for the Gulf of Alaska. If the relationship to the pycnocline is functional, a shift to a similar depth habitat during the LGM
could result in a δ²⁰O offset of up to 1% during the LGM. Thus any downward shift of the depth habitat of *G. bulloides* toward the pycnocline, or decrease in the regional salinity - δ⁴⁰O₈ slope at the LGM, would result in an overestimate of LGM cooling based on δ⁴⁰O₈.

The offshore δ¹³C gradient, measured in LGM *G. bulloides* shells, is compared with equilibrium calcite values (δ¹³Cₐ) predicted from water column δ¹³C measurements on dissolved inorganic carbon in the same transect [Ortiz et al. 1996]. The watercolumn δ¹³Cₐ are well correlated with dissolved nitrate, and thus we consider the isotopic data to be a good proxy for upper ocean nutrient gradients in this region. We emphasize gradients because absolute δ¹³C values are affected by (1) the LGM δ¹³Cₐ decrease relative to the Holocene ocean (about -0.4‰; Curry and Crowley [1987]), (2) the modern δ¹³Cₐ decrease due to input of anthropogenic CO₂ into the upper ocean (-0.6±0.2‰ in this region [Ortiz et al. 1996]), and (3) the potential for δ¹³C disequilibria in *G. bulloides*. For equation (3), we model the carbon isotopic disequilibrium in the δ¹³C of *G. bulloides* as a function of calcification temperature, Tₐ, following Ortiz et al. [1996]:

\[
\delta^{13}C_a = \delta^{13}C + 2.07e^{-0.2/10}
\]  

Equation (6)

We use the LGM modern analog SST values derived from the foraminiferal faunas to estimate Tₐ.

Simulating Wind-Driven Upwelling

Upwelling, which injects nutrients into the upper ocean and thus supports biological productivity, is driven by the winds in two ways in this eastern boundary setting. First, along-shore winds from the north drive offshore Ekman transport. Coastal upwelling replaces the water moved offshore. Active coastal upwelling is limited to about 50 km offshore, mostly over the continental shelf, but its effects can extend farther offshore as coastal nutrients are advected seaward. Second, divergence of winds (wind stress curl) drives upwelling in the open ocean. In the northern hemisphere, positive (cyclonic) wind stress curl induces oceanic upwelling, whereas negative (anticyclonic) wind-stress curl results in downwelling. These mechanisms often reinforce each other but are not strictly linked. Changes in one mechanism can be decoupled from the other.

To isolate these two effects of coastal and open-ocean upwelling we calculated Ekman transport and wind stress curl using wind fields from the National Center for Atmospheric Research (NCAR) atmospheric regional climate model (RegCM). The version of the RegCM used here has 13 vertical levels and 60-km grid spacing over a 3000 x 3000 km domain centered at 38°N, 116°W (i.e., the interior of the model domain are NW=49.6°N, 137.3°W; NE=49.6°N, 94.6°W; SW=23.9°N, 130.1°W; SE=23.9°N, 101.9°W). Model wind fields from Hostetler et al. [1994] were sampled for 60 days to calculate offshore Ekman transport and wind stress curl. Perpetual January and July simulations were run using control (0 ka) and LGM (18 ka) boundary conditions derived from the coarse resolution COHMAP general circulation model (GCM) runs of Kutzbach and Guetter [1986].

We calculated wind stress curl on the model grid using a centered, finite difference scheme:

\[
\text{curl} \vec{\tau} = \left( \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right)
\]

that approximates curl at grid location based on \( \vec{\tau}_x \) and \( \vec{\tau}_y \) at four neighboring grid points separated by distances \( \Delta x \) and \( \Delta y \) of 120 km [Nelson, 1977]. We did not employ the overlapping-grid method of Bakun and Nelson [1991] because unlike their irregularly spaced observations, our model wind fields are relatively smooth on a regularly spaced 60-km grid. Our wind stress curl estimates were interpolated to 0.6° by 0.6° resolution for graphic presentation using the nearest neighbor method, yielding resolution similar to the seasonal maps of Bakun and Nelson [1991].

Results

Comparison of Modern and Glacial Foraminiferal Faunas

Modern and LGM foraminiferal percentage data appear in Table 4, and the abundances of dominant species are illustrated in Figure 3. Left-coiling *N. pachyderma* (Figure 3a) and *G. bulloides* (Figure 3d) dominate the LGM fauna, accounting for >70% of the foraminifera at each site. This combination resembles the modern subpolar fauna of the Gulf of Alaska [Sautter and Thunell, 1989]. High percentages of these species occur in our LGM transect as far west as 130°W, some 650 km offshore. In contrast, left-coiling *N. pachyderma* and *G.
Globigerina glutinata, were found at roughly equal percentages in both the modern and LGM data sets. Another, the deep-dwelling Globorotalia scitula [Ortiz et al. 1996] decreased in abundance in the LGM samples relative to the modern ones (Figure 3).

Transitional taxa, including N. dutertrei, decreased at LGM relative to present in the cores near the coast. Peak abundance of right-coiling N. pachyderma (30%) is similar in the modern and LGM assemblages (Figure 3h) but moved offshore during the LGM at the expense of modern subtropical species (Orbulina universa and Globigerinoides ruber) (Figure 3).

The LGM planktonic foraminiferal fauna at 42°N records expansion of subpolar conditions as far west as 130°W, trending to transitional waters offshore. These data are consistent with ice-age cooling across the entire transect. Similar to the modern distribution, the LGM fauna associated with cooler water occurred near the coast, while the warmer-water LGM fauna was found offshore. Some of the decrease in O. universa and G. ruber observed could reflect greater dissolution in LGM sediment samples than in modern sediment trap samples. If so, our results would overestimate the extent of ice-age cooling far offshore.

Modern Analog Sea Surface Temperatures

The modern analog SST estimates derived from the modern sediment trap faunas track atlas values at the coastal sites but overestimate SST at the site farthest offshore. The presence of O. universa and G. ruber drive the anomalous warmth in the offshore estimate [Ortiz and Mix, this issue]. These species are rare in N. Pacific core tops from midlatitudes, probably because they are highly sensitive to dissolution. Because the calibration data set is composed of partially dissolved core tops, this "no-analog" bias shows up in the well-preserved sediment trap samples. We expect that this bias is not a problem for the LGM samples.

The best modern analogs for the LGM California Current foraminifera are from core top sediments in the Gulf of Alaska, although some analog samples come from similar latitudes in the North Atlantic. The dissimilarity coefficients for each core were small (well below the empirical cutoff of 0.2), so the analogs are excellent (Table 5).

At the LGM, the annual average modern analog SST was 3.3±1.5°C cooler than modern atlas SST at 42°N (Table 5, Figure 4). SST remained coolest near the coast and increased offshore. The LGM offshore thermal gradient was similar to today's (about 0.3°C/degree longitude). Given the 1.5°C error of the method, there was no statistically significant structure to the LGM - modern SST difference across the transect.

Oxygen Isotopes and Sea Surface Temperatures

The δ18O of G. bulloides at the LGM was higher near the coast and lower offshore (Figure 5, Table 5). This gradient agrees with the sense of temperature gradients implied by the glacial fauna. Predictions of the oxygen isotopic composition of equilibrium calcite, δ18Ocalc, based on modern atlas SST and
LGM δ18O data suggests denser water (colder and/or saltier) near degree longitude (r²=0.72, n=10). The offshore slope of the gradient calculated from the LGM samples was -0.13% δ18O / degree longitude (r²=0.79, n=10) at these sites. Salinities, yield a zonal gradient in δ18O of -0.09% δ18O / degree longitude (r²=0.72, n=10). The offshore slope of the gradient calculated from the LGM samples was -0.13% δ18O / degree longitude (r²=0.79, n=10) at these sites. A similar southward geostrophic flow as at present.

Assuming all of the observed gradients in δ18O arose from temperature, the associated offshore thermal gradient would be 0.5°C to 0.6°C / degree longitude. This is about twice the temperature gradient at present, and twice that estimated from the LGM fauna (+0.3°C / ° longitude). Possible explanations could be that (1) the LGM salinity gradient was steeper than the modern one, (2) the LGM salinity/δ18O, slope was steeper than

**Figure 3.** Planktic foraminifera species percentages across the transect at 42°N: (a) left coiling *N. pachyderma*, (b) *G. glutinata*, (c) *N. dutertrei*, (d) *G. bulloides*, (e) *G. scitula*, (f) *O. universa*, (g) *G. quinqueloba*, (h) right-coiling *N. pachyderma* and (i) *G. ruber*. Solid squares denote LGM horizon. Open squares denote modern sediment trap data based on flux-weighted averages of seasonal data reported by Ortiz and Mix [1992].

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**Table 5.** LGM Modern Analog Method SST and LGM *G. bulloides* (300-355 μm) Stable Isotope Measurements Across the Multitracers Transect

<table>
<thead>
<tr>
<th>Core Name</th>
<th>Sample Depth, cm</th>
<th>Longitude, °W</th>
<th>Mean Dissimilarity</th>
<th>LGM SSTb</th>
<th>Modem SSTb</th>
<th>LGM- Present SST Change</th>
<th>δ18O, %oPDB</th>
<th>δ13C, %oPDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>6706-2</td>
<td>259-260</td>
<td>124.94</td>
<td>0.06</td>
<td>9.0</td>
<td>11.4</td>
<td>-2.8</td>
<td>2.79</td>
<td>-0.03</td>
</tr>
<tr>
<td>W8709A-13PC</td>
<td>275-276</td>
<td>125.75</td>
<td>0.07</td>
<td>10.0</td>
<td>12.3</td>
<td>-2.3</td>
<td>2.97</td>
<td>-0.27</td>
</tr>
<tr>
<td>W8809A-53GC</td>
<td>168-169</td>
<td>126.26</td>
<td>0.05</td>
<td>9.8</td>
<td>12.6</td>
<td>-2.8</td>
<td>3.16</td>
<td>0.20</td>
</tr>
<tr>
<td>W8809A-21GC</td>
<td>140-141</td>
<td>126.91</td>
<td>0.09</td>
<td>8.8</td>
<td>12.9</td>
<td>-4.1</td>
<td>2.70</td>
<td>0.07</td>
</tr>
<tr>
<td>W8709A-08PC</td>
<td>22-23</td>
<td>127.68</td>
<td>0.05</td>
<td>9.3</td>
<td>13.3</td>
<td>-4.0</td>
<td>2.81</td>
<td>-0.06</td>
</tr>
<tr>
<td>W8809A-29GC</td>
<td>156-157</td>
<td>129.00</td>
<td>0.06</td>
<td>9.8</td>
<td>13.8</td>
<td>-4.0</td>
<td>2.28</td>
<td>0.07</td>
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<tr>
<td>W8809A-31GC</td>
<td>15-16</td>
<td>130.01</td>
<td>0.10</td>
<td>10.6</td>
<td>14.1</td>
<td>-3.5</td>
<td>2.67</td>
<td>-0.09</td>
</tr>
<tr>
<td>W8809A-57GC</td>
<td>22-23</td>
<td>130.62</td>
<td>0.05</td>
<td>9.8</td>
<td>14.2</td>
<td>-4.4</td>
<td>2.52</td>
<td>0.37</td>
</tr>
<tr>
<td>W8709A-01BC</td>
<td>21-22</td>
<td>131.96</td>
<td>0.09</td>
<td>11.8</td>
<td>14.4</td>
<td>-2.6</td>
<td>2.19</td>
<td>0.82</td>
</tr>
<tr>
<td>W8909A-48GC</td>
<td>17-18</td>
<td>132.67</td>
<td>0.09</td>
<td>11.8</td>
<td>14.5</td>
<td>-2.7</td>
<td>1.82</td>
<td>0.87</td>
</tr>
</tbody>
</table>

*Based on foraminiferal faunas using the modern analog method, associated errors are ±1.5°C.

bInterpolated to core locations from Levitus [1982].
the modern slope, or (3) *G. bulloides* lived deeper in the water column nearer the coast during the LGM.

The $\delta^{18}O$ of LGM *G. bulloides* is higher by $\sim3\%$ than modern $\delta^{18}O_s$, predicted for the sea surface (Figure 5). After accounting for a $1.3\%$ ice volume effect on mean ocean $\delta^{18}O_s$, we can estimate an upper limit for the LGM temperature change across the transect, assuming the slope of the regional salinity/$\delta^{18}O_s$ relationship was unchanged, and *G. bulloides* calcified in the mixed layer (its present habitat at these sites as recorded by MOCNESS plankton tows). This estimate suggests the magnitude of the LGM cooling at these sites could have been $4°-6°C$ at most. For comparison, we have plotted the foraminiferal modern analog LGM SST estimates as equivalent $\delta^{15}O$ predictions using the same assumptions (Figure 5).

A $4°-6°C$ cooling based on the oxygen isotope data is at the upper statistical limit of the $3.3°\pm1.5°C$ cooling estimated by the modern analog faunal method. However, it is likely some of this apparent $4°-6°C$ cooling reflects local increases in salinity driven by stronger ice-age upwelling, or a change of the depth habitat of *G. bulloides*. For example, the deviations between the modern analog paleotemperatures expressed as $\delta^{18}O$ and the *G. bulloides* $\delta^{18}O$ measurements can be minimized in a least squares sense, yielding a residual of $0.09\%$ (approximately our $\delta^{18}O$ machine precision) using a $\delta^{18}O$ offset of $-0.75\pm0.05\%$. This offset is smaller than the $1\%$ offset relative to surface waters attributed to modern *G. bulloides* in the Gulf of Alaska due to a depth habitat near 100 m [Zahn et al. 1991a]. Thus, while *G. bulloides* $\delta^{18}O$ helps to constrain the zonal thermal gradient it does not provide a unique measure of the absolute temperature change.

### Carbon Isotopes and Nutrient Gradients

In the absence of active upwelling, modern surface waters (offset to the LGM mean) yield $\delta^{13}C_c$ predictions near $2.5\%$ with small variation across the transect (Figure 6). Active upwelling brings nutrient-rich waters from around 70 m depth to the surface (Figure 6). This reduces surface $\delta^{13}C_c$ to values near those at 100 m at the same site. The modern $\delta^{13}C_c$ at 100 m increases offshore by about $1\%$. This shift reflects shoaling of the nutrient line in response to southward geostrophic flow and local wind forcing.

The $\delta^{13}C$ of LGM *G. bulloides* range from $-0.27\%$ near the coast to $0.87\%$ near 132.5°W (Figure 6, Table 5). After disequilibrium effects are estimated and removed (equation 3), the mean $\delta^{13}C$ of *G. bulloides* approximates water column $\delta^{13}C_c$, derived from measurements of water column $\delta^{13}C_{sec}$ corrected for the anthropogenic $\delta^{13}C_{se}c$ decrease and the mean ocean's glacial-interglacial $\delta^{13}C_{se}c$ shift. The offshore gradient in $\delta^{13}C$ remains, suggesting large offshore nutrient gradients as at present. Westward translation of the LGM $\delta^{13}C$, gradient relative to the present gradient suggests westward translation of the associated nutrient gradients, perhaps coupled to an increase in net upwelling as far west as 130°W.

### Shell Accumulation Rates and Foraminiferal Productivity

The accumulation rates of left-coiling *N. pachyderma* and *G. bulloides* shells near 126°W are much greater at the LGM than in the modern sediment traps (Figure 7). This cannot be an artifact of dissolution, because the LGM sediment samples are...
Figure 6. Carbon isotopic composition (δ13C) of G. bulloides from glacial sediments across the 42°N transect. The magnitude of the carbon isotopic disequilibrium (physiological offset, Δδ13Cp) in G. bulloides is estimated using equation 3. Modern δ13C values at 42°N based on measurements from Ortiz et al. [1996] are plotted for reference after being offset for the glacial δ13C shift of -0.4‰ and the anthropogenic shift of -0.6‰.

more dissolved than the modern sediment trap samples. Given potential errors in sediment accumulation rates associated with timescale uncertainties, we hesitate to interpret structure in the decreasing offshore accumulation rates. Given the consistency of the result, however, the net increase relative to modern fluxes appears robust. Because these species are heterotrophic, they are sensitive to food supply and thus to productivity (Ortiz et al. 1996). We interpret the higher LGM accumulation rates of these species as due to higher productivity of the heterotrophic foraminifera. This is consistent with the carbon isotopic evidence for westward expansion of nutrient supplies noted above.

Ekman Transport and Coastal Upwelling

The seasonal offshore Ekman transport simulated by the RegCM for modern boundary conditions captures the basic structure and magnitude of the coastal upwelling seasonal cycle in the California Current (Figure 8). Consistent with observations [Huyer, 1983], north of 40°N, coastal upwelling is seasonal, strong in July but absent (or downwelling) in January. Between 30°N and 40°N, coastal upwelling persists throughout the year, but is strongest in summer. South of 30°N both observations and the model record roughly constant coastal upwelling throughout the year.

North of 45°N, model-simulated offshore Ekman transport exceeds observed values for both seasons. This feature probably reflects edge effects at the northern boundary of the model domain. Peaks in observed offshore transport between 35°N and 40°N are displaced southward by the model by 1°-2° latitude. This most likely reflects difficulty defining coastline shape precisely in the gridded model.

Simulated offshore Ekman transport at the LGM was lower in both seasons than it is at present (Figure 8). North of 42°N the model predicts coastal downwelling in both seasons. Major reductions in summer upwelling occur north of 40°N, and winter downwelling occurs as far south as 33°N. South of 33°N, predicted changes in coastal upwelling are relatively small, probably within the range of model uncertainties. The overall
reduction in coastal upwelling at the LGM is associated with simulated along the western boundary south of 32°N, and near the coast in both seasonal simulations, especially south of curl for modern January (Figure 9a) and July (Figure 9d) capture upwelling in this area. The RegCM simulations of wind stress positive curl drives strong upwelling east of 128°W. South of 126°W along our 42°N transect, curl is negative, yielding in wind stress curl over the California Current. In winter, west offshore, consistent with observations. Positive curl persists near the coast in both seasonal simulations, especially south of about 40°N.

The model simulations are not perfect, however. North of 47°N, simulated curl is always positive, unlike observations. This is probably an edge effect near the northern limit of the RegCM domain. Similarly, edge effects of positive curl simulated along the western boundary south of 32°N, and negative curl simulated along the southern boundary, are unrealistic. The modern July simulation also indicates local zones of intense convergence (negative curl) near the upwelling front at 38°N and 32°N. These features are not present in the maps of Bakun and Nelson [1991]. Given these apparent weaknesses in the model simulations, we only interpret broad features, and rely on difference maps between modern and ice-age conditions. The hope is that model biases common in both runs would tend to cancel, minimizing the net bias in the difference maps.

The LGM wind stress curl simulations suggest enhanced positive curl in offshore regions for both the January and July simulations (Figures 9b and 9e). LGM-minus-modern difference maps confirm that ice-age curl was more positive offshore in both January and July. In the LGM January simulation, curl decreased near the coast north of 33°N. Thus, on an annual average basis, the model simulations suggest a net westward translation of curl-driven upwelling offshore between 30°N and 42°N during the LGM, relative to conditions at present.

**Discussion**

The Glacial Temperature Decrease

Our results suggest that the mean annual SST at 42°N during the LGM was 3.3±1.5°C cooler than present. This temperature estimate is consistent with the radiolarian faunal temperature estimates of Moore [1973] and Moore et al. [1980] in three cores near our locations. Similarly, Prahl et al. [1995] compared temperature estimates based on $U^*_p$ and radiolarian faunal estimates in one core studied here (W8709A-8PC) and inferred an LGM temperature decrease of 4.0°±1.5°C, similar to our estimate. The agreement between these methods is somewhat surprising. Measurements of the $U^*_p$ index in sediment traps at the same sites used here yielded an annual temperature of 10.6±1.1°C with no significant offshore gradient [Prahl et al. 1993]. This estimate is significantly cooler than the 12°-15°C annual mean SST at these sites. Prymnesiophyte algae which generate the alkenone signal bloom in the spring and summer and reside within the thermocline, rather than at the sea surface [Prahl et al. 1993]. In contrast, the radiolarian transfer function generates temperatures based on the calibration of Holocene faunas against mean annual sea surface temperature. According to Prahl et al. [1995], these two seemingly different methods produce similar temperature estimates because in the North Pacific, mean annual SST over the range 0°-15°C is equivalent to the summer temperature at the pycnocline.

Sabin and Pisias [1996] used the same radiolarian transfer function as Prahl et al. [1995] in a meridional transect from 35° to 55°N. Their transect included two cores used here (W8709A-8PC and W8709A-13PC). We supplement the two published LGM radiolarian temperature estimates at 42°N with one from W8809A-31GC (radiolarian taxonomy courtesy of M. Webber, Oregon State University). The resulting radiolarian SST estimates yield LGM cooling of 4.2±1.5°C, 4.4±1.5°C, and 2.4±1.5°C in the three sites relative to modern atlas values, indistinguishable from the foraminiferal-based estimate of 3.3±1.5°C cooling in this region (Figure 4).

The 3°-4°C cooling we estimate was roughly constant across the entire east-west transect. Our estimate is smaller than the
Figure 9. Simulated wind stress curl for the California Current region. Results are from (a) modern January, (b) glacial January, (c) glacial January-modern January, (d) modern July, (e) glacial July, and (f) glacial July-modern July. Contours are in 10^4 dynes cm^2. Cyclonic wind stress curl (positive values, solid contours) drives oceanic upwelling. Anticyclonic wind stress curl (negative values, dashed contours) drives oceanic downwelling. The calculations are based on winds from the NCAR RegCM runs of Hostetler et al. [1994].
5°-10°C cooling suggested by Mortyn et al. [1996] from δ¹⁸O of G. bulloides in the Southern California Borderland sediments, but larger than the 1.5°C cooling based on the U₁₃⁷, temperature index in ocean drilling program (ODP) Site 893 from the Santa Barbara Basin [Herbert et al. 1995]. These differences may in part reflect regional temperature variations, although Mortyn et al. [1996] did not attempt to constrain the effect of upwelling-related salinity variations on δ¹⁸O, which would likely reduce the amplitude of their inferred cooling.

Zonal Thermal Gradients and Southward Flow

At 42°N, LGM temperatures remained coolest near the coast and increased offshore. This pattern is similar to the modern zonal thermal gradient at this latitude and suggests that a southward flowing California Current was still present during the LGM. The steeper offshore δ¹⁸O gradient relative to the modern water column δ¹⁸O gradient at 42°N may suggest a stronger density gradient, and if so, geostrophy would require enhanced southward advection. However, this possibility should be viewed with caution due to uncertainties in the slope of the LGM S-δ¹⁸O relationship and foraminiferal depth habitats.

Southward flow at 42°N requires that the LGM polar front remained north of our sites. Had the Polar front shifted south of our locations, local wind forcing would have been more heavily influenced by the cyclonic Aleutian low. In response, a poleward flowing eastern boundary current of the subarctic gyre would have replaced the California Current over our sites. Under such conditions, one would expect to see cold, nutrient-enriched water throughout the transect, with a zonal thermal gradient reversed from that observed (i.e. warmer temperatures near the coast with a gradual offshore cooling). This pattern, which is similar to the modern wintertime regime at 42°N, would be associated with offshore oceanic upwelling in the LGM subarctic gyre.

Enhanced Glacial Nutrient Content

We observed a >1‰ δ¹³C enrichment in LGM G. bulloides shells offshore relative to those near the coast (Figure 6). This enrichment does not appear to be related to the organism's physiological carbon isotopic disequilibrium as predicted for temperature effects [Ortiz et al. 1996]. Paleoceanographic factors that could cause the enrichment include variations in air-sea equilibration state, nutrient content, or some combination of both effects. Local equilibration with the atmosphere seldom reaches completion in surface waters due to differences in the time of contact with the atmosphere (order of months) relative to the time required for isotopic equilibration (order of years to decades) and competing biological carbon transports. If δ¹³Cwater were fully equilibrated with the atmosphere (holding other effects constant), it would follow a slope near -0.14‰ δ¹³Cwater / °C so that the δ¹³Cwater in colder water would be higher than in warmer water [Kroopnick, 1974]. In this case, we would expect G. bulloides shells closer to the coast to record δ¹³C values >0.4‰ higher than those offshore. This is not the case. A better explanation of increasing δ¹³C offshore is that surface waters rich in nutrients are low in δ¹³CDIC, whereas those depleted in nutrients are high in δ¹³CDIC. The LGM offshore gradient of δ¹³C in G. bulloides thus implies higher nutrient content near the coast and lower nutrient content offshore.

The LGM δ¹³C gradient in G. bulloides across 42°N is steeper than the modern water column gradient at the sea surface. It is similar to the modern δ¹³C, gradient at 100 m (Figure 6). The offshore subsurface enrichment trend in the modern ocean begins east of 128W°. In the LGM samples, high δ¹³C values are not encountered east of 130W°. If G. bulloides occupied a surface habitat, LGM surface waters were greatly enriched in nutrients relative to modern ones across the entire transect. If G. bulloides occupied a depth habitat closer to 100 m (consistent with its apparent modern Gulf of Alaska habitat), then offshore waters were enriched in nutrients down to ~100m, and coastal waters carried roughly the same nutrient content as modern waters. In either case, LGM nutrients in offshore regions of the California Current at 42°N were most likely slightly to greatly enhanced relative to their modern values. Variations in LGM wind forcing could cause such a nutrient change by (1) enhancing coastal upwelling due to greater offshore Ekman transport, (2) enhancing oceanic upwelling resulting from greater wind stress curl, or (3) enhancing southward flow due to stronger basin scale wind stress curl.

We discount the first mechanism because the RegCM results suggest that coastal upwelling north of 35°N decreased in the California Current during the LGM (Figure 8), a result which is consistent with lower accumulation rates of coastal diatoms [Sancetta et al. 1992] and marine organic carbon [Lyle et al. 1992]. RegCM simulations support the second mechanism, enhanced LGM wind-stress curl in the California Current relative to modern conditions (Figure 9). This implies that enhanced oceanic upwelling supplied nutrients from below to increase the nutrient content of offshore LGM waters, decrease their δ¹³C composition, and indirectly produce the observed increase in offshore accumulation rates of heterotrophic foraminiferal shells by increasing prey density.

The third potential mechanism for increasing the nutrient content of the LGM California Current is enhanced southward flow. As noted previously, the offshore gradient of LGM δ¹³O is consistent with enhanced southward advection during the LGM. The coarse resolution atmospheric GCM results of Kutzbach and Guetter [1986] suggest that North Pacific winds were stronger and displaced southward at the LGM. These changes could increase the proportion of cold, nutrient-rich water flowing from the LGM North Pacific Current, into the equatorward LGM California Current, as opposed to the poleward LGM Alaskan Current. This would shift the character of the LGM California Current toward more subarctic conditions and result in the upward tilting of isopycnals, a geostrophic readjustment to enhanced southward flow. A similar concept explains years with anomalous subarctic zooplankton biomass in the modern California Current [Chelton, 1982; Chelton and Davis, 1982; Chelton et al. 1982].

The net results of both the second and third mechanisms would be to cool the surface waters of the LGM California Current and increase its nutrient content. These changes would in turn produce waters with lower δ¹³C values farther offshore and increase the offshore shell accumulation rates of heterotrophic foraminifera. As a result, we cannot definitively
distinguish between these mechanisms. Mechanisms 2 and 3 are not entirely independent, however, because large-scale variations in wind stress curl provide the forcing for the Sverdrup balance as well as for local open-ocean upwelling [Chelton, 1981, 1982].

Community Ecology of the Glacial California Current

The foraminiferal fauna of the LGM California Current at 42°N is similar to that of the modern Gulf of Alaska. Does the ecologic shift recorded by the foraminifera reflect the plankton community as a whole? Perhaps.

Marine organic carbon accumulation rates in some of the sites studied here were lower during the LGM than at present, suggesting lower carbon export [Lyle et al. 1992]. Accumulation rates of Chaetoceros spores, diatom indicators of the modern coastal upwelling ecosystem, were also low during the LGM [Sanetza et al. 1992]. Ice-age pollen assemblages were dominated by pine and mountain hemlock, in contrast to the modern assemblage of oak, redwood, and alder [Sanetza et al. 1992]. Loss of redwood and alder at the LGM suggests a reduced moisture supply due to loss of summer coastal fog. Fog is generated by relatively warm atmosphere over colder (upwelled) oceanic waters. These results all suggest lower coastal upwelling during the LGM.

Reduction of coastal upwelling, coupled with our evidence for higher nutrient content and foraminiferal shell fluxes along most of the 42°N transect during the LGM, suggest an ecosystem similar to that of the modern Gulf of Alaska. The modern California Current is a high-nutrient, high-chlorophyll, high-export ecosystem. The dominant primary producers in this environment are large diatoms [Hood et al. 1990]. These diatoms, and the macrozooplankton that graze on them, export a relatively large fraction of the total biological productivity as fecal pellets and sinking particles. In contrast, the Gulf of Alaska is a high-nutrient, low-chlorophyll, low-export system. An active microbial loop, composed of a variety of small autotrophs and heterotrophs, makes recycling more efficient here than in the California Current [Miller et al. 1991]. In such systems, a smaller fraction of organic matter sinks to the seafloor.

The decrease in export productivity of the LGM California Current at 42°N is ultimately linked to changes in the physical environment. However, these physical changes did not simply cause the biological interactions of the modern oceanic community to run more slowly. Rather, the physical changes appear to have resulted in the replacement of the high-export flux, modern coastal upwelling community with a low-export flux, subarctic, open-ocean upwelling community.

Conclusions

Foraminiferal species and isotopic data from 10 sediment cores suggest the magnitude of the LGM temperature decrease across the California Current at 42°N during the LGM was 3.3 ±1.5°C. The cooling was roughly constant across the entire transect. Temperatures remained coolest near the coast and increased offshore, similar to the modern annual average zonal thermal gradient. These findings suggest that the equatorward flowing California Current was still present at 42°N during the LGM, and that the polar front must have remained north of this latitude band.

Cooling was likely a response to stronger open-ocean upwelling and southward advection driven by higher wind stress curl. Coastal upwelling decreased at 42°N during the LGM.

LGM waters of the California Current were relatively high in nutrients offshore (based on carbon isotope data) and low in biomass due to more intense grazing by microorganisms (based on reduced organic carbon accumulation rates and increases in heterotrophic plankton). This suggests that during the LGM the plankton community of the northern California Current was similar to the modern plankton community of the Gulf of Alaska.

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