Millennial scale changes in sea surface temperature and ocean circulation in the northeast Pacific, 10–60 kyr BP

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[1]   A new centennial-scale Mg/Ca temperature record from the California margin (ODP Site 1017E) reveals large millennial-scale oscillations between 10 to 60 kyr. This record indicates that sea surface temperature on the California Margin warmed rapidly on the deglacial by $7.4 \pm 0.8°C$, and was preceded by a pre-Bølling temperature oscillation of $2.6 \pm 1.2°C$. Millennial-scale events of the last glacial episode were marked by sea surface temperature oscillations of between 3 and 7°C on the California margin, and interstadials were associated with an increase in surface water salinity. The data are consistent with evidence for a glacial southward shift in the polar jet stream and concomitant strengthening of the relatively cold, fresh California Current during stadial events. The data also support previous hypotheses suggesting a tight coupling between the North Atlantic and northeast Pacific response to climate instability of the last glacial episode.

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1.   Introduction

[2]   The role of the Pacific Ocean in global climate change over the last glacial cycle remains a fundamental issue. A key question is the magnitude and timing of sea surface temperature (SST) changes in the northeast Pacific, a region far removed from the direct effects of continental ice sheets, and the implications of SST changes for regional and global teleconnections on both orbital and millennial time scales. Outside of the North Atlantic region, large millennial-scale oscillations were identified in Santa Barbara Basin climate records of the last glacial episode (27–60 kyr [*Behl and Kennett*, 1996; *Hendy and Kennett*, 1999]), where their remarkable similarity to the Dansgaard-Oeschger (D/O) events in Greenland ice core records [*Dansgaard et al.*, 1993] led those authors to suggest that abrupt climate events were transmitted immediately from the North Atlantic region to the northeast Pacific via atmospheric teleconnections. D/O-type events have also been recognized in high-resolution climate records throughout the northern Hemisphere [*Kotilainen and Shackleton*, 1995; *Porter and An*, 1995; *Hughen et al.*, 1996; *Cannariato and Kennett*, 1999; *Hendy and Kennett*, 2000; *Peterson et al.*, 2000; *Seki et al.*, 2002; *Asmerom et al.*, 2010]; however, the amplitude and regional expression of D/O signals remains poorly characterized. In marine records from the California margin, it is clear that D/O-type oscillations were associated with potentially large SST changes; however, foraminiferal $\delta^{18}O$ records preclude the identification of the relative contributions of temperature and salinity. Furthermore, estimates of SST differ significantly in these cores based on different methods. In the best-known core from the region, Santa Barbara Basin ODP Site 893A, SST estimates of cooling at the last glacial maximum range from 2 to 4°C based on the alkenone unsaturation index ($U^{k'}_{37}$) [*Herbert et al.*, 1995, 2001], to 8°C based on planktonic foraminiferal $\delta^{18}O$ [*Hendy and Kennett*, 1999], and to 11°C based on foraminiferal transfer functions [*Hendy and Kennett*, 2000]. These differences may result from factors such as inaccuracies in the estimates of ice volume and salinity effects on $\delta^{18}O$, ecological and preservational biases on the floral and faunal proxies [*Hendy*, 2010], or other factors. Regardless, understanding the source of these differences is critical in interpreting how global climate signals are transmitted to the northeast Pacific.

[3]   Discrepancies in estimates of the timing of glacial-interglacial SST changes along the California margin also have implications for mechanisms of climate change. Within the limits of the existing age models, foraminiferal isotopes and faunal abundance changes indicate that SST changes in the Southern California Borderlands region occurred in phase with global ice volume, suggesting that a strong atmospheric teleconnection rapidly transmitted temperature changes between ocean basins [*Cannariato and Kennett*, 1999; *Hendy and Kennett*, 1999, 2000]. Conversely, results from alkenone unsaturation ratios indicate that surface waters warmed thousands of years in advance of ice sheet melting, and that the timing of the temperature lead varied spatially along the margin [*Herbert et al.*, 2001; *Seki et al.*, 2002]. In the southern California Borderlands region (Santa Barbara and Tanner Basins), the temperature lead during the deglaciation was ~10–15 kyr based on $U^{k'}_{37}$

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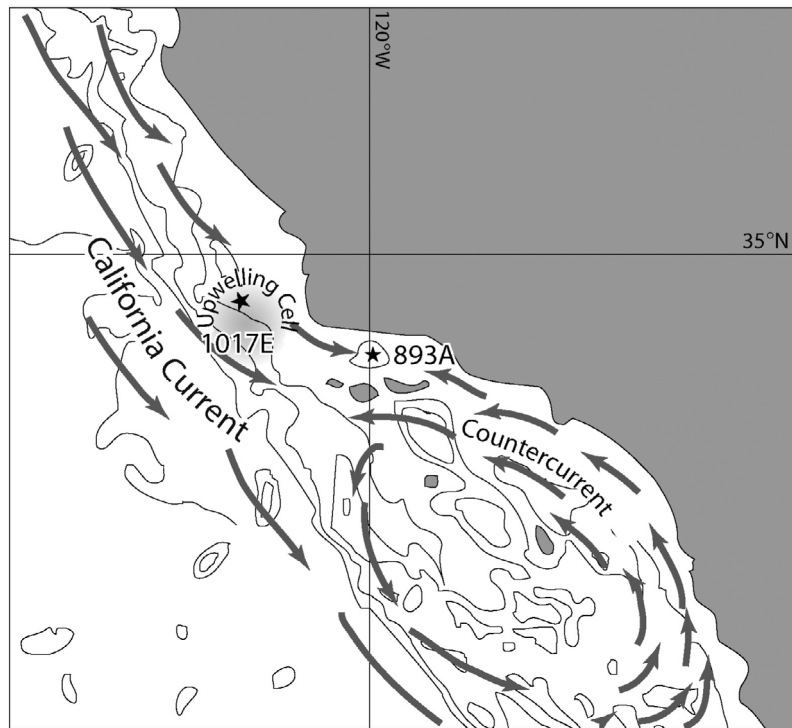
Figure 1. Location of ODP Site 1017E on the Santa Lucia slope, California (34°32′N, 121°6′W; 24.9 m core length; 956 m water depth) and ODP Hole 893A in Santa Barbara Basin. Generalized location and direction of the California Current and Countercurrent are shown with arrows [*Winant et al.*, 2003]. A persistent upwelling cell lies off Point Conception/Point Arguello. Upwelling favorable winds occur year-round but are most intense in the spring and summer [*Lynn*, 1967; *Harms and Winant*, 1998].

records, and the lead was smaller in the core of the California Current off northern California and absent in the Baja region. *Herbert et al.* [2001] hypothesized that early warming off southern California resulted from a shut-down of the cold California Current and decrease in upwelling along the margin during glacial intervals. This is in contrast to previous authors [*Thunell and Mortyn*, 1995; *Mortyn et al.*, 1996; *Mortyn and Thunell*, 1997; *Hendy and Kennett*, 1999], who suggested, based on foraminiferal faunal and $\delta^{18}O$ records, that cool glacial SSTs recorded in Santa Barbara Basin were due to a strengthening of the California Current and/or an increase in the rate of coastal upwelling along the California margin. Distinguishing between these or alternate hypotheses requires accurate estimates of the phasing and amplitude of millennial-scale temperature events on the California margin. The lack of a concordant paleotemperature record for California margin sediment cores highlights the need for an alternate independent approach that can be directly related to the oxygen isotope record.

[4] Planktonic foraminiferal Mg/Ca has been validated as a paleotemperature proxy in downcore samples [*Hastings et al.*, 1998; *Elderfield and Ganssen*, 2000; *Lea et al.*, 2000; *Anand et al.*, 2003]. Unlike $\delta^{18}O$, Mg in foraminiferal calcite is not affected by changes in $\delta^{18}O$-water. Although several recent studies argue for a more significant effect of salinity on foraminiferal Mg/Ca, particularly at very high salinity conditions [*Arbuszewski et al.*, 2010; *Martínez-Botí et al.*, 2011], culturing experiments indicate

that change in seawater salinity has a secondary effect of $5 \pm 3\%/psu$ [*Nürnberg et al.*, 1996; *Lea et al.*, 1999; *Kisakürek et al.*, 2008]. The Mg/Ca proxy also has the advantage that it is measured in the same phase as foraminiferal $\delta^{18}O$, unlike non-foraminiferal temperature proxies. Thus it can be used in conjunction with $\delta^{18}O$ to isolate the effects of temperature from those of ice volume and salinity in the same samples. In oceanic margin regions surface salinity effects on $\delta^{18}O$ may be considerable due to hydrographic complexity and proximity to freshwater run-off from continental areas. Mg/Ca paleothermometry has the potential to provide a paleotemperature record and to determine the phasing of temperature relative to the $\delta^{18}O$ record, which provides the primary climatological framework for marine sediment cores.

[5] Here, we present a centennial-scale *Globigerina bulloides* Mg/Ca temperature record from ODP Site 1017E on the California Margin. This record provides a quantitative estimate of the amplitude and timing of sea surface temperature changes across millennial scale climate events of the last glacial episode and the deglaciation from a region that is highly sensitive to abrupt climate changes. Together with published oxygen isotopic data from the same core, we use the Mg/Ca temperature record to extract the $\delta^{18}O$-water signal and interpret the extent of salinity changes on surface waters on the California Margin from 60 kyr through the deglaciation and into the Holocene. The resulting SST and surface salinity records provide inferences about ocean and
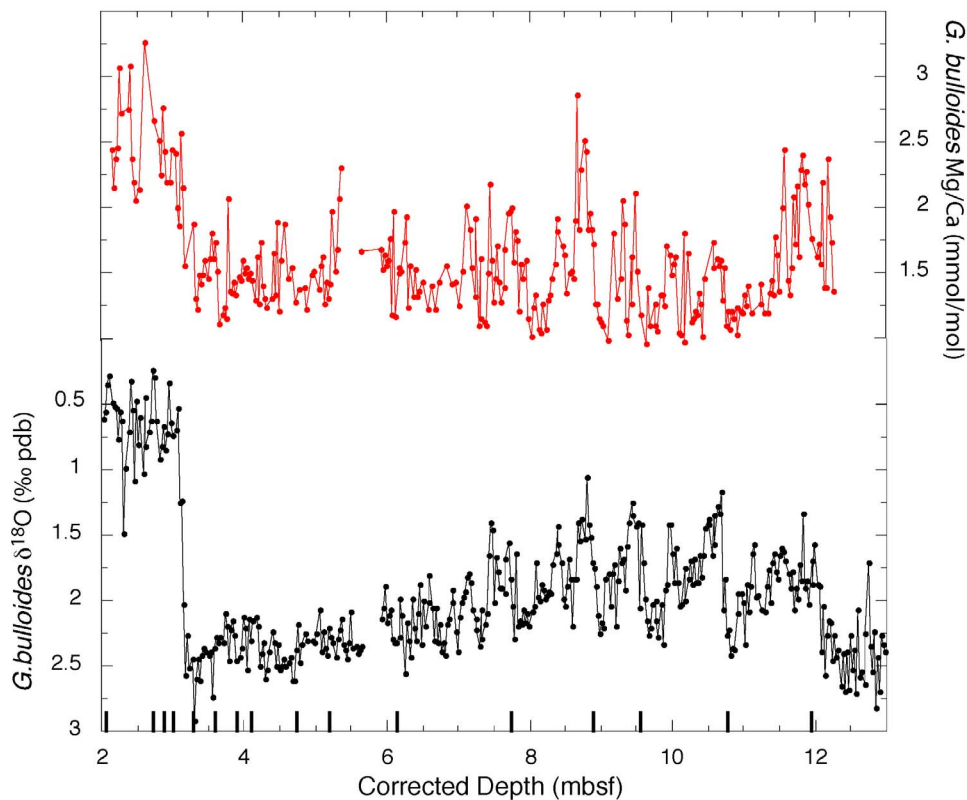
Figure 2. Hole 1017E planktonic foraminiferal (*G. bulloides*) oxygen isotope [*Kennett et al.*, 2000; *Hendy et al.*, 2004] and Mg/Ca data plotted versus void-corrected depth. Mg/Ca analyses were analyzed on the same samples as those for oxygen isotopes; ~10% of the Mg/Ca points are based on two or more analyses. Age control points are indicated with the black bars (see Table 1 for age model details).

atmospheric circulation changes in the northeast Pacific over abrupt climate transitions between 60 and 10 kyr.

2. Methods

2.1. Core Site and Chronology

[6] ODP Hole 1017E was recovered from the Santa Lucia Slope off Point Arguello, California (34°32′N, 121°6′W; 24.9 m core length; 956 m water depth; Figure 1). Persistent upwelling above the site leads to a present-day seasonal range in SST of 9°C to 20°C with a mean annual SST of 14.4°C [*Locarnini et al.*, 2006]. The site lies near the confluence of the equatorward flowing California Current and the poleward flowing Southern California Countercurrent, and the regional hydrography is dominated by the interplay between these two currents. During the spring and summer, the northward position of the North Pacific High pressure cell contributes to predominantly northerly winds, seasonal upwelling and a relatively strong California Current. During the late summer and fall, the North Pacific High is displaced southward as the Aleutian Low strengthens, resulting in low winds, decreased upwelling and a greater influence of the subtropical Countercurrent [*Brink and Muensch*, 1986; *Lynn and Simpson*, 1987; *Bograd et al.*, 2002; *Winant et al.*, 2003].

[7] For this study, we continuously sampled the upper 12.5 m of Hole 1017E at 3 to 5 cm intervals. Sample depths are reported using the shipboard void-corrected depth scale,

which removes all core voids greater than 2.5 cm [*Kennett et al.*, 2000]. The average sample resolution of the record is 190 years, with the highest resolution of 100 years between 17.7 and 20.3 kyr, and the lowest sample resolution of 370 years between 59.2 and 60 kyr (Figure 2). We adopt a previously established chronology for Site 1017E which is based on eleven calendar age calibrated AMS ^{14}C dates in the upper 4.7 m of the core ranging in age from 8,810 to 21,390 yr BP [*Hendy et al.*, 2004]. Below 5 m, the chronology is based on linear interpolation between six climatic event datum levels identified in the Santa Barbara Basin ODP 893A *Neogloboquadrina pachyderma* coiling record and correlated with 1017E (Table 1) [*Hendy et al.*, 2004] (see Figure 2 for age control points). The ODP 893A chronology is tied to the GISP2 ice core chronology; error on the GISP2 chronology ranges from ±1400–3300 years over the interval of comparison [*Stuiver and Grootes*, 2000]. Estimated errors (1 SD) on the radiocarbon-constrained part of the chronology are ±550 yr at 9 kyr BP, ±500 yr at 17 kyr BP and ±720 yr at 22 kyr BP. Based on the chronology, the average sedimentation rate over the whole record at Site 1017E is 23 ± 12 cm/kyr, the average sedimentation rate between 2 and 5 m core depth is 25 cm/kyr and the average sedimentation rate between 5 and 12.5 m is 19 cm/kyr. At Site 1017, as evidenced by decreasing percent $CaCO_3$ and increasing percent organic carbon in samples younger than 10 kyr [*Hendy et al.*, 2004], dissolution in the upper part of the core has led to low foraminiferal abundances in sediments

Table 1. Published Radiocarbon and Climatic Event Datums for ODP Site 1017E[a]

Core, Section	Sample Interval	Age (^{14}C years)	Climatic Event Datums	Depth, Void-Corrected (mbsf)	Age (years)
1H-2	54–57	8500 ± 100		1.97	8810
1H-2	63–66	9010 ± 50		2.05	9220
1H-2	132–135	11880 ± 50		2.72	13,150
1H-3	0–3	12900 ± 50		2.89	14,120
1H-3	12–15	13050 ± 60		3.00	14,660
1H-3	51–54	14390 ± 60		3.38	17,020
1H-3	69–72	15540 ± 80		3.55	17,720
1H-3	111–114	16660 ± 70		3.95	19,010
1H-3	126–129	17190 ± 80		4.09	19,620
1H-4	12–15	17670 ± 100		4.44	20,170
1H-4	39–42	18730 ± 120		4.70	21,390
2H-2	45–48		Start IS 8	7.7	38,400
2H-3	21–24		Start IS 11	8.85	42,600
2H-3	102–105		Start IS 12	9.59	45,400
2H-4	81–84		Start IS 14	10.77	52,200
2H-5	57–60		Start IS 17	11.92	58,300
2H-5	108–111		MIS 3/4 boundary	12.39	64,090

[a]*Hendy et al.* [2004].

younger than ∼9 kyr. However, in sediments older than ∼9 kyr (2.0 mbsf), foraminifera appear visually well-preserved, without evidence of pitting or fragmentation. The studied section ranges in age from 10 to 60 kyr, and covers several important climatic transitions including correlatives to the Younger Dryas and Bølling-Allerod events, Termination I and numerous stadial/interstadial oscillations of Marine Isotope Stage 3 (Figure 2).

2.2. Methods for Mg/Ca Analysis

[8] Site 1017E δ^{18}O data is presented elsewhere [*Kennett et al.*, 2000; *Hendy et al.*, 2004]. For this study, Mg/Ca analyses were conducted on monospecific samples of *G. bulloides* picked from the same samples as for previously published δ^{18}O. *G. bulloides* was selected for Mg/Ca analysis for its consistent abundance, near-surface habitat and the availability of a previously published isotope record. In some regions, *G. bulloides* abundance is highly seasonal and closely associated with productivity and upwelling [*Ganssen and Kroon*, 2000]. Previous studies have also suggested that *G. bulloides* Mg/Ca may be higher than predicted from δ^{18}O, possibly due to isotopic disequilbrium effects in this species [*Elderfield and Ganssen*, 2000; *Martínez-Botí et al.*, 2011]. However, in nearby Santa Barbara Basin, sediment trap studies indicate that *G. bulloides* dominates the flux of planktonic foraminifera year-round and is not restricted to upwelling events. Sediment trap studies also indicate that *G. bulloides* δ^{18}O and Mg/Ca consistently reflect water conditions at approximately 20–30 m depth [*Kincaid et al.*, 2000; *Pak and Kennett*, 2002; *Pak et al.*, 2004]. For each analysis approximately 30 individuals were picked from the >150 um size fraction, weighed, and gently crushed between glass plates to expose inner chambers to the cleaning reagents. Although it would be preferable to analyze foraminifera from a narrow size range to reduce the possibility of ontogenetic effects on Mg/Ca, shell size does not have a significant effect on the Mg/Ca to SST relationship in *G. bulloides* [*McConnell and Thunell*, 2005] and a larger size fraction was necessary to obtain sufficient numbers of foraminifera for analysis. Foraminifera samples were cleaned for Mg/Ca following the UCSB standard foraminiferal trace-

and minor-element cleaning protocol, which includes both oxidative and reductive steps [*Lea et al.*, 2000; *Martin and Lea*, 2002]. Oxidative and reductive cleaning have been shown to reduce Mg/Ca and increase reproducibility by removing contaminant Mg associated with organic and authigenic phases, respectively [*Martin and Lea*, 2002; *Pena et al.*, 2005; *Bian and Martin*, 2010].

[9] Strong seasonal upwelling and high sedimentation rates due to high productivity and terrestrial input characterize the site. In addition, the slope location of ODP Site 1017E has led to several small turbiditic intervals between 5 and 7 mbsf [*Irino and Pedersen*, 2000]. Following the protocol of *Irino and Pedersen* [2000] intervals with >0.08 Zr/Ti were interpreted to be turbiditic and not included in the record. Of the 419 samples, 21 were omitted from the record as turbiditic intervals.

[10] Cleaned samples were simultaneously spiked and dissolved in 500 μL of a multielement spike and analyzed using a Thermo Finnigan Element2 sector inductively coupled plasma mass spectrometer (ICP-MS). Mg/Ca was determined at UCSB by the isotope dilution/internal standardization method [*Lea and Martin*, 1996; *Lea et al.*, 2000]. Analytical precision of Mg/Ca based on 28 replicate analyses of a consistency standard is estimated at ±1.1% (1σ).

[11] Because detrital material has been indicated as a Mg contaminant [*Barker et al.*, 2003; *Lea et al.*, 2006], care was taken to manually remove non-calcite contaminant grains from samples during the cleaning process following the procedure of *Barker et al.* [2003]. Calcite recovery after the cleaning process averages 45%; samples with less than 10% calcite recovery were omitted from the record. Overall, fewer than 5% of the individual analyses were rejected based on low recovery.

3. *G. bulloides* Mg/Ca SST Results

[12] *G. bulloides* Mg/Ca values at Site 1017E range from a low of 1.0 mmol/mol during the last glacial episode (∼39.6 kyr) to a high of 3.2 mmol/mol in the Holocene (12.4 kyr; Figure 2). The *G. bulloides* Mg/Ca record
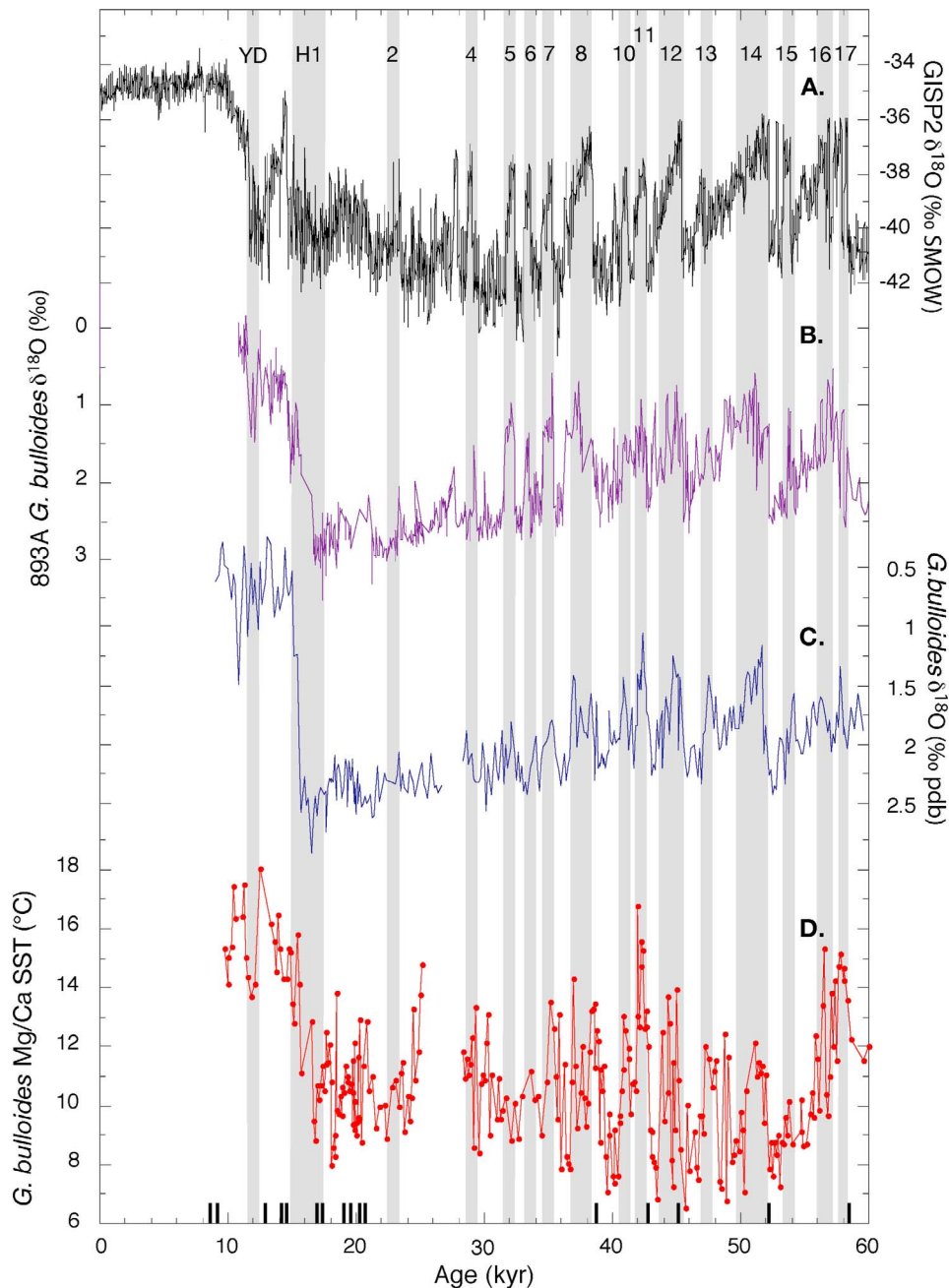
Figure 3. Site 1017E SST record plotted versus age. The age model is after *Hendy et al.* [2004] and age control points are indicated with the black boxes (see Table 1 for details). The correlative Younger Dryas, Heinrich Event 1, and Marine Isotope Stage 3 interstadial events are marked with gray bars. (a) GISP2 δ^{18}O-ice [*Stuiver and Grootes*, 2000], (b) Site 893A *G. bulloides* δ^{18}O [*Hendy and Kennett*, 2000], (c) Site 1017E *G. bulloides* planktonic foraminiferal δ^{18}O [*Hendy et al.*, 2004] and (d) Site 1017E *G. bulloides* Mg/Ca SST.

from 1017E strongly resembles that of the δ^{18}O record (Figures 2 and 3) [*Hendy et al.*, 2004]. The Mg/Ca record shows abrupt, high amplitude, millennial-scale oscillations in MIS 3, with stadial Mg/Ca $\sim$1.0–1.2 mmol/mol and interstadial Mg/Ca $\sim$2.0–2.5 mmol/mol. During the deglaciation, Site 1017E Mg/Ca values increase from 1.3 ± 0.4 (16.8 to 16.6 kyr) to 2.4 ± 0.2 mmol/mol (15.6 to 15.4 ka) within 1200 yr, and continue to rise to a maximum of 3.2 mmol/mol at the Allerød-Younger Dryas boundary. The

Younger Dryas interval is represented by an abrupt decrease in Mg/Ca from 3.2 mmol/mol to 2.2 ± 0.15 mmol/mol.

[13] Mg/Ca was converted to SST using the culture-based *G. bulloides* calibration equation of *Mashiotta et al.* [1999]: SST = ln(Mg/Ca)/0.474)/0.107 (SE = $\pm 0.8°$C). This equation has been verified in sediment trap *G. bulloides* from Santa Barbara Basin, where it accurately reconstructs near-surface temperatures in a four-year time series [*Pak et al.*, 2004]. In Santa Barbara Basin *G. bulloides* is the most

abundant species year-round, and core top Mg/Ca values from this species reflect annual average temperatures [*Pak et al.*, 2004]. In the Site 1017E record, Mg/Ca derived temperatures indicate that SSTs ranged from $8.1 \pm 0.7°C$ during MIS 3, between 48.6 and 46.0 kyr, to $17.0 \pm 0.6°C$ in the Holocene (10.4 to 11.3 kyr).

[14] Although the Mg/Ca record shows a strong similarity to the corresponding *G. bulloides* $\delta^{18}O$ record, there are also significant differences. For instance, a notable difference occurs between the Mg and $\delta^{18}O$ records in the character and timing of the deglacial warming. At Site 1017, the most positive $\delta^{18}O$ values occur at ~16.5 kyr. Whereas this time is also a local Mg/Ca SST minimum, the lowest Mg/Ca values occur some 2000 years earlier at 18.3 kyr, and are followed by a brief but prominent 1400 year oscillatory warming event of ~2°C (Figure 3). The Mg temperature record also indicates a gradual increase in temperature from the early deglaciation (16.5 kyr) to the beginning of the Younger Dryas (12.6 kyr), in contrast to the oxygen isotope record, which indicates an immediate decrease to minimum Bølling values between 15.1 and 14.7 kyr, followed by relatively stable values (Figure 3). The apparent young age of the Younger Dryas is within the error (±600 yr) of the chronology of this part of the record [*Hendy et al.*, 2004].

[15] On millennial time scales, the last glacial episode (60 to 25 kyr) is marked by large abrupt oscillations in temperature of ~1–2.5 kyr in duration. These oscillations are on average ~4–5°C in amplitude; the largest event, from 43.0 to 41.2 kyr, represents a change of $5.5 \pm 1.5°C$ (Figure 3). Millennial-scale oscillations in $\delta^{18}O$ have been previously identified in high resolution California margin sediments, including Site 1017E and Santa Barbara Basin, where their strong similarity to D/O events suggests that they are synchronous [*Hendy and Kennett*, 2000; *Hendy et al.*, 2002, 2004]. At Site 1017E, millennial-scale oscillations in Mg/Ca and $\delta^{18}O$ are synchronous, and are also apparently synchronous with D/O events in the Greenland ice core record within the error limits of the chronology [*Stuiver and Grootes*, 2000; *Hendy et al.*, 2004]. All of the interstadial events between IS2 and IS17 are represented in the 1017E Mg/Ca record, with the exception of IS3, which is missing in a 1017E core break, IS5, which is muted in the 1017E $\delta^{18}O$ record, and IS9, which is also absent from the 1017E $\delta^{18}O$ record (Figure 3).

[16] An event presumed to be synchronous with the Younger Dryas chronozone is characterized by a point-to-point cooling of $4.2 \pm 0.6°C$ in the 1017E Mg/Ca SST record. This event is not seen in the *G. bulloides* $\delta^{18}O$ record (Figures 2 and 3), although it is clearly recorded in the $\delta^{18}O$ record of *N. pachyderma* [*Hendy et al.*, 2004] at the same site. This strongly suggests that surface salinity changes significantly affected the $\delta^{18}O$ record of near surface-dwelling *G. bulloides*, such that cooling was counterbalanced by a decrease in surface salinity that did not affect thermocline-dwelling *N. pachyderma*.

4. Discussion

4.1. Hydrographic Changes on the California Margin During the Last Glacial Episode

[17] The discovery of millennial scale variability in Santa Barbara Basin sediments, and its striking similarity to the Greenland ice core temperature record, led previous authors to suggest that the California Margin recorded Northern Hemisphere-wide variability, and that this signal was transmitted rapidly via atmospheric teleconnections [*Behl and Kennett*, 1996; *Hendy and Kennett*, 1999, 2000]. However, the assumptions involved in quantifying temperature from $\delta^{18}O$ left uncertainty as to the magnitude of the millennial-scale temperature changes on the California margin. The Mg/Ca record from Site 1017 indicates that millennial-scale stadial and interstadial events of the last glacial episode identified from $\delta^{18}O$ are synchronous with large, $4.5 \pm 1.5°C$ changes in SSTs that occurred abruptly within 100 to 200 years (Figure 3). Both Mg/Ca and $\delta^{18}O$ of planktonic foraminifera reflect the temperature of calcification; however, $\delta^{18}O$-calcite also bears the signal of the $\delta^{18}O$-water. In marginal settings, $\delta^{18}O$-water can be strongly affected by freshwater run-off and evaporation/precipitation, as well as by salinity differences in water masses and changes in continental ice volume. Using the *G. bulloides* Mg/Ca-based temperatures and the published $\delta^{18}O$ of the coeval samples [*Hendy et al.*, 2004], we have calculated the $\delta^{18}O$-water variations over the past 60 kyr at Site 1017. Following previous protocol, we used the *Bemis et al.* [1998] *Orbulina LL* paleotemperature equation (T = 16.5 − 4.80($\delta^{18}O$-calcite − $\delta^{18}O$-water)) and a regional $\delta^{18}O$/salinity relationship of the Southern California Bight of $\delta w = (0.39S) − 13.23$ [*Spero and Lea*, 1996]. *Bemis et al.* [2002] indicate that the *Orbulina* LL equation yields the most realistic temperatures for glacial age *G. bulloides* in nearby Santa Barbara Basin. To remove the effect of continental ice volume changes on $\delta^{18}O$-water, we calculated a global mean $\delta^{18}O$-water record from the centennial-scale sea level record of *Siddall et al.* [2003], assuming a $\delta^{18}O$-water change of 0.1‰ for every 10 m of sea level change [*Lea et al.*, 2002]. The high-resolution *Siddall et al.* [2003] record covers the interval from 60–22 kyr; for the interval from 10 to 22 kyr, we used the low-resolution global mean $\delta^{18}O$-water record of *Waelbroeck et al.* [2002]. We interpolated both the *Waelbroeck et al.* [2002] and the *Siddall et al.* [2003] records to 200 years to match the sample resolution of the 1017 record. The resulting global mean $\delta^{18}O$-water record was subtracted from the 1017E $\delta^{18}O$-water record to obtain the $\Delta\delta^{18}O$-water record (Figure 4).

[18] The millennial-scale stadial and interstadial temperature oscillations of the last glacial episode are clearly apparent in the $\delta^{18}O$-water record, with stadials corresponding to more negative $\delta^{18}O$-water and interstadials corresponding to more positive $\delta^{18}O$-water values (Figure 4). Similarly, the Younger Dryas interval is apparent as a sharp decrease of 0.4 ± 0.2‰ in $\delta^{18}O$-water at 12.6 kyr. The inverse relationship between $\delta^{18}O$-water and temperature reflects the strong influence of both temperature and salinity on the isotopic record, with warm interstadials associated with relatively high salinity surface waters. Two different mechanisms may account for abrupt changes in SST on the California Margin during the last glacial: changes in upwelling intensity and changes in relative strength of the California Current and Southern California Countercurrent [*Mortyn et al.*, 1996; *Mortyn and Thunell*, 1997; *Herbert et al.*, 2001; *Hendy et al.*, 2004; *Hendy*, 2010]. At present, Site 1017 lies beneath an active upwelling cell; an increase in past upwelling intensity could decrease SSTs by up to
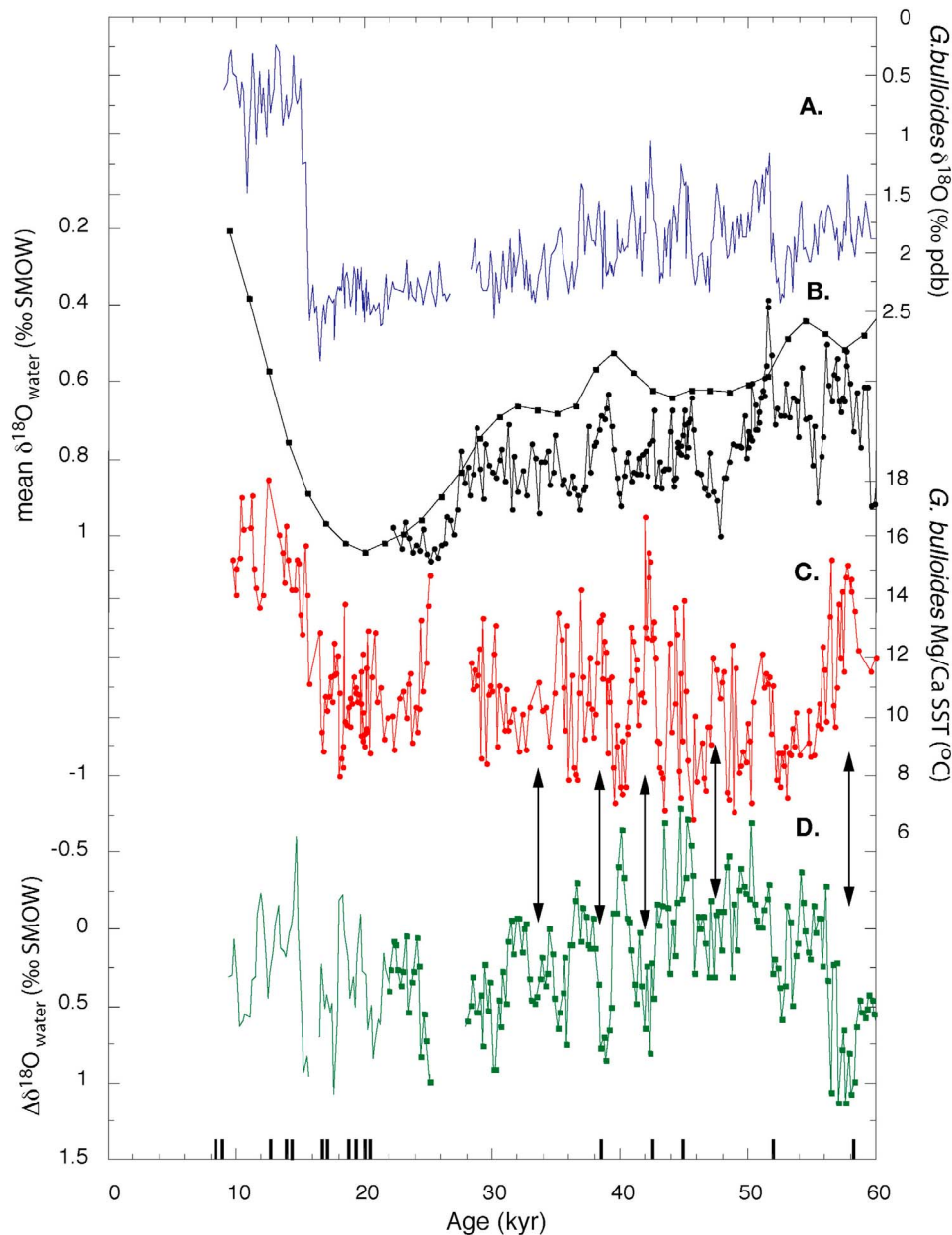
Figure 4. Calculated *G. bulloides* Mg/Ca SST and δ^{18}O-water compared with measured *G. bulloides* δ^{18}O [*Hendy et al.*, 2004] plotted by age. The arrows indicate where interstadial warm events correspond with increased salinity as interpreted from the δ^{18}O-water record. (a) Site 1017E *G. bulloides* δ^{18}O [*Hendy et al.*, 2004], (b) Global mean δ^{18}O-water record of *Waelbroeck et al.* [2002] (black squares) and calculated from the *Siddall et al.* [2003] sea level curve (black circles), (c) Site 1017E *G. bulloides* Mg/Ca SST calculated from the δ^{18}O and the *G. bulloides* paleotemperature equation of *Mashiotta et al.* [1999]. (d) Site 1017E $\Delta\delta^{18}$O-water record calculated by subtracting the global mean δ^{18}O-water record of *Waelbroeck et al.* [2002] (10–22 kyr) from the 1017E δ^{18}O record (green line) and mean δ^{18}O-water record calculated from the sea level record of *Siddall et al.* [2003] (green points). The *Waelbroeck et al.* [2002] and *Siddall et al.* [2003] records were interpolated every 200 years to achieve similar resolution to the 1017E record.

10°C [*Locarnini et al.*, 2006]. Previous work indicates that coastal California regions experienced greater productivity during the last glacial relative to interglacials, likely due to enhanced upwelling [*Mortyn and Thunell*, 1997;

Hendy et al., 2004]. However, on the millennial scale, there is no clear relationship between stadials and enhanced productivity at Site 1017; in fact, interstadial events were generally more productive than stadials [*Hendy et al.*,

2004]. Furthermore, our δ^{18}O-water record indicates that sea surface salinity decreased during stadial events, whereas increased upwelling would likely increase surface salinity. We favor millennial scale changes in the relative strengths of the California Current and subtropical Countercurrent as the primary explanation for our observed stadial-interstadial changes in SST and salinity, although we recognize that increased glacial upwelling could enhance the magnitude of the observed SST changes.

[19] At present, the core site is affected by the seasonal interplay between the relatively cold, fresh California Current and the warmer, more saline, Southern California Countercurrent. During the summer the northerly position of the North Pacific High results in a stronger California Current at the expense of the warm subtropical Countercurrent, whereas during the fall and winter, the North Pacific High migrates southward, and the less saline California Current weakens, resulting in a more northerly influence of more saline subtropical Countercurrent water along the California Margin [Huyer, 1983; Harms and Winant, 1998; Bograd et al., 2002]. The 1017 δ^{18}O-water record implies that this scenario is a plausible mechanism for observed millennial-scale variability during the last glacial episode and the Younger Dryas. The peak-to-peak change in δ^{18}O-water between stadial and interstadials is ~0.5–1.0‰, implying salinity changes of ~1 to 2.5 psu. The calculated salinity change is in part dependent on the choice of δ^{18}O/salinity relationship used. Using a regional δ^{18}O/salinity relationship for the Southern California Bight of 0.4‰ δ^{18}O per 1 psu [Spero and Lea, 1996] implies a salinity change of 1.25 to 2.5 psu, whereas using a global mean δ^{18}O/salinity relationship of 0.5‰ δ^{18}O per 1 psu [Broecker, 1989] implies a smaller salinity change of 1 to 2 psu.

[20] Salinity variability in the California Current is primarily controlled by longshore flow, with equatorward advection freshening upper ocean waters, and poleward advection increasing the salinity [Schneider et al., 2005]. Site 1017E lies below the present-day high salinity gradient region of the California Current, where upper ocean salinity has ranged from 33.15 to 33.7 in the last 40 years [Schneider et al., 2005]. We note that our reconstructed salinity variations are larger than this modern range. However, the long-term mean salinity of California coastal surface waters ranges from <33.0 off Mendocino, near the core of the California Current, to >34.6 off Baja California, which is dominated by the subtropical Countercurrent [Lynn, 1967]. Large changes in advection could conceivably increase the range of salinity variability at Site 1017, as the boundary between the California Current and subtropical Countercurrent shifted. Furthermore, large (0.6) variations in salinity have been reported from recent observations in the Gulf of Alaska [Overland et al., 1999; Schneider et al., 2005]. We suggest that changes in the salinity of the source waters of the California Current, along with changes in the relative strength of the California Current and subtropical Countercurrent, may account for the range of salinity reconstructed from our δ^{18}O-water record.

[21] Previous work supports the idea that cold events were accompanied by a major increase in the advection of sub-arctic waters along the California Margin via the California

Current, which shifted the influence of the subtropical Countercurrent southward of Site 1017. Thunell and Mortyn [1995] and Mortyn et al. [1996] hypothesized that a southward shift of the North Pacific High during the last glacial contributed to a strengthening of the California Current and a decrease in SSTs along the California Margin, while Hendy and Kennett [2000] and Hendy et al. [2002] suggest a similar mechanism accounted for cold SSTs during millennial-scale stadial events in the Santa Barbara Basin during Marine Isotope Stage 3.

[22] Variations in the positions of North Pacific atmospheric highs and lows control not only surface currents but also regional patterns of evaporation and precipitation. Colder polar temperatures of the last glacial episode would likely have shifted the jet stream and resultant storm tracks southward, increasing precipitation in southwestern North America. Evidence for this effect is observed in New Mexico cave deposits [Asmerom et al., 2010], as well as in a high-resolution pollen record from Santa Barbara Basin [Heusser, 1998], both of which indicate relatively more arid conditions during interstadial events and wetter conditions during stadial events. Increased precipitation during stadial events could also account for some of the observed δ^{18}O-water changes in the ODP 1017E record, by reducing salinity in coastal California waters. At present, coastal run-off due to precipitation is relatively low in Southern California; however, episodic flood layers are evident in Holocene Santa Barbara Basin cores [Schimmelmann et al., 2003]. Both the marine SST and the terrestrial precipitation records support the hypothesis that D/O events in Greenland ice cores were associated with a reorganization of Northern Hemisphere atmospheric circulation, and that the resultant repositioning of the North Pacific high and low pressure systems led to both SST and water mass changes in the Northeast Pacific. Oceanic conditions in the northeast Pacific appear to have responded abruptly despite the large distance from the direct effects of Northern Hemisphere ice sheets and North Atlantic circulation changes.

4.2. Amplitude and Phasing of Deglacial Sea Surface Temperature Changes on the California Margin

[23] The timing and amplitude of temperature changes on the California margin has strong implications for the mechanisms of climate change. Whereas foraminiferal δ^{18}O and sediment records suggest that the California margin is tightly coupled to Northern Hemisphere climate changes via atmospheric teleconnections [Thunell and Mortyn, 1995; Behl and Kennett, 1996; Hendy and Kennett, 1999], other investigators have suggested that the North Pacific deglacial response may have been more regional, reflecting the sensitivity of the region to the movement of oceanographic fronts [Herbert et al., 2001; Kiefer and Kienast, 2005]. The 1017 Mg/Ca record provides an opportunity to examine phase relationships in a single core within a single faunal group, and to compare the Mg/Ca SST record with other proxy records of temperature from the same core.

[24] The G. bulloides Mg/Ca record at Site 1017 indicates that sea surface temperatures on the California margin experienced a large, rapid warming during the deglaciation (Figure 3). The initial rise in SST occurred at 18.1 ± 0.5 kyr, ~1.5 kyr prior to the initial decrease in δ^{18}O that marks the
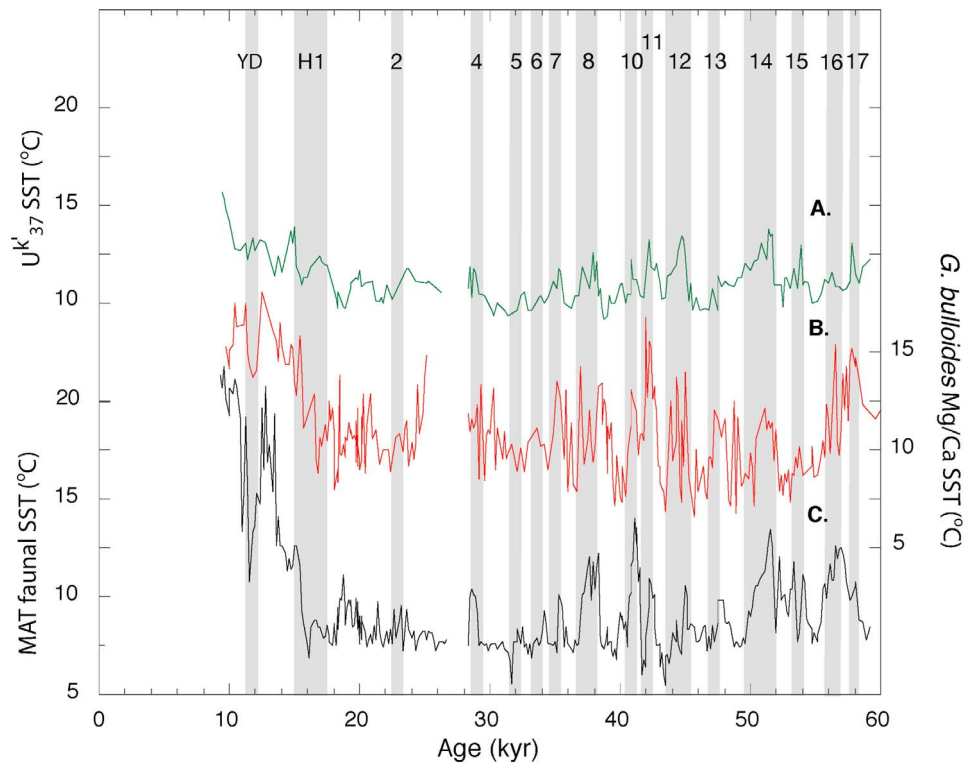
Figure 5. Comparison between SST proxies from Site 1017. (a) $U^{k'}_{37}$ data from *Seki et al.* [2002], (b) *G. bulloides* MAT faunal transfer function data from *Hendy and Kennett* [2000] and (c) *G. bulloides* Mg/Ca SST calculated from the Mg/Ca data from this study using the *G. bulloides* calibration equation of *Mashiotta et al.* [1999].

beginning of the deglaciation. This initial warming marks the onset of a 2.6 ± 1.2°C oscillatory event that lasted 1.5 kyr; it was followed by a rapid warming of 5.8 ± 1.6°C that began at 16.5 ± 0.5 kyr and that lasted ~1.1 kyr (Figure 3). The entire deglacial warming was 7.4 ± 0.8°C, from an initial low of 8.5 ± 0.4°C at 18.1 kyr to 15.8 ± 0.4°C in the Bølling at 14.6 kyr. The magnitude of deglacial warming was approximately equal to the modern seasonal range of SSTs in the region. Site 1017 represents the first Mg/Ca SST record from the northeast Pacific. Few other Mg/Ca records from the greater North Pacific region exist, however, two Mg/Ca SST records from the subarctic northwest Pacific indicate slightly smaller deglacial warming of 4–6°C [*Sarnthein et al.*, 2006; *Kiefer et al.*, 2001]. Several factors may account for the smaller subarctic warming, including choice of species for analysis and oceanographic setting. Analyses of subarctic *N. pachyderma* may reflect subsurface habitat or stronger seasonality than the midlatitude *G. bulloides* at Site 1017. Alternatively, enhanced glacial upwelling at Site 1017 could potentially amplify the deglacial SST change.

[25] At Site 1017, previously published work affords us the opportunity to directly compare SST records based on different proxies, including $U^{k'}_{37}$ [*Seki et al.*, 2002], foraminiferal faunal transfer functions [*Hendy and Kennett*, 1999] and Mg/Ca (this study). Because all of the temperature proxies were completed on the same core, the proxies can be

directly compared on the same age model, and without effects of spatial or temporal differences in SST (Figure 5). As expected, all of the temperature proxies indicate colder temperatures during the last glacial episode than during the Holocene. D/O- type millennial-scale variability during Marine Isotope Stage 3 (MIS3) is clear in each of the proxy temperature records, with D/O oscillations represented from IS4 to IS17. Although all of the temperature proxies indicate similar timing of MIS3 oscillations, the size of the MIS3 peaks differs. The foraminiferal-based proxies show larger temperature oscillations throughout the record than do alkenone-based SSTs. In addition, $U^{k'}_{37}$ temperatures are generally warmer at 1017E than those indicated by planktonic foraminiferal proxies. Of the three proxies, foraminiferal faunal temperatures show the greatest warming during the deglaciation: 12 ± 0.7°C from the last glacial maximum to the early Holocene. This is largely due to the cold glacial temperatures as determined by foraminiferal faunal assemblages; faunal temperatures and Mg/Ca temperatures are similar in the early Holocene. $U^{k'}_{37}$-based temperatures indicate a small, gradual warming of 2.8 ± 0.8°C between 18.7 and 11.6 ± 1 kyr (Figure 5). Mg/Ca indicates a warming of 7.4 ± 0.8°C between 18.1 and 14.6 kyr, about halfway between the two other proxy estimates. Similar discrepancies between $U^{k'}_{37}$ and foraminiferal based paleotemperature proxies have been reported for other middle and high latitude sites, and previous authors have suggested that

alkenone-producing phytoplankton in these environments may be recording warm season SSTs rather than mean annual average temperatures [*Bard*, 2001]. A compilation of Holocene Mg/Ca and $U_{37}^{k'}$ SST records from the eastern equatorial Pacific also exhibits significant differences between the two proxies, which are likely due to differences in seasonal fluctuations in coccolithophorids and foraminifera [*Leduc et al.*, 2010]. Coccolithophorids have a relatively narrow thermal tolerance and therefore $U_{37}^{k'}$ records may reflect bloom events during the season of highest productivity [*Leduc et al.*, 2010]. Foraminifera have seasonal fluctuations but often remain abundant year-round, as is the case with *G. bulloides* in central California waters today [*Kincaid et al.*, 2000].

[26] Although the Mg/Ca SST record at Site 1017 exhibits warming ~1.5 kyr prior to the major deglacial decrease in $\delta^{18}O$, there is no evidence of the 10 kyr or more lead indicated by $U_{37}^{k'}$ SST records on the California Margin [*Herbert et al.*, 2001; *Seki et al.*, 2002]. Early deglacial warming inferred from $U_{37}^{k'}$ SSTs on the California margin has previously been used to infer a shut-down of the California Current during the last Glacial Maximum (LGM) in response to a displacement of wind systems due to the presence of the Laurentide Ice Sheet [*Herbert et al.*, 2001]. At Site 1017E, $U_{37}^{k'}$ results indicate glacial SSTs occur episodically between 50 and 19 kyr, after which the $U_{37}^{k'}$ temperatures rise gradually to peak warm temperatures around 10 kyr [*Seki et al.*, 2002]. Because both the $U_{37}^{k'}$ and Mg/Ca records are derived from the same core, there can be no offset due to age model disagreement. However, the reduced warming in the $U_{37}^{k'}$ temperature record makes it difficult to identify the initiation of the warming within the overall relatively stable temperatures of the LGM. Based on the 1017E $U_{37}^{k'}$ record, deglacial warming began at ~19 kyr [*Seki et al.*, 2002], 3.5 kyr prior to the abrupt $\delta^{18}O$ decrease that marks the onset of the Bølling. The apparent SST lead implied by the $U_{37}^{k'}$ record may be due to the low magnitude of the $U_{37}^{k'}$ signal. Alternatively, the differences between the alkenone and foraminiferal-based proxies may reflect resuspension and post-depositional transport of fine-grained organic particles. Sand-sized foraminifera generally are deposited directly beneath their site of origin, whereas the finer-grained alkenone bearing sediments may be selectively advected long distances [*Bard*, 2001]. Resuspension and lateral advection of sediments has been indicated as a factor in asynchroneity of alkenone and foraminiferal ages from the continental slope off west Africa, and Site 1017E is in a similar region of upwelling and vigorous current flow [*Mollenhauer et al.*, 2003].

4.3. Deglacial Atmospheric and Oceanic Reorganization in the North Pacific

[27] The 1017E Mg/Ca and $\delta^{18}O$ records indicate that the extratropical Pacific experienced a large SST increase during the deglaciation, and that the temperature change was accompanied by a significant change in sea surface salinity. These observations provide evidence for a reorganization of oceanic/atmospheric circulation in the Northeast Pacific during the deglaciation that led to a shift in precipitation zones and/or the boundary between the California Current and the subtropical Countercurrent.

[28] At Site 1017E, SST increased ~8°C between 18 and 15 kyr. Over the same time interval, planktonic foraminiferal $\delta^{18}O$ decreased by ~2.5‰. The estimated global seawater $\delta^{18}O$-water change due to ice volume change on the deglacial is −1.0 ± 0.1‰ [*Schrag et al.*, 1996; *Adkins et al.*, 2002; *Schrag et al.*, 2002]. Removing the ice volume and temperature components of the $\delta^{18}O$ record leaves a residual $\delta^{18}O$-water increase of ~0.9‰ (Figure 4) and implies an increase in surface water salinity of ~1.8–2.2 (using the regional calibration) between 18 and 15.5 kyr.

[29] The observed $\delta^{18}O$-water increase at Site 1017E during the deglaciation is similar in direction and amplitude to the millennial-scale $\delta^{18}O$-water oscillations observed during interstadial events of the last glacial episode, and this increase is consistent with an increase in the relative strength of warm, saline poleward flow of the subtropical Countercurrent during deglaciation. Previous investigators have suggested that the California Current weakened during the deglacial in response to a northward shift of the North Pacific High as the high latitudes warmed [*Thunell and Mortyn*, 1995; *Hendy and Kennett*, 1999]. Our observations are consistent with this interpretation.

[30] In addition, the increase in surface water $\delta^{18}O$ on the California margin may have been amplified by a decrease in precipitation as atmospheric and oceanic circulation patterns shifted as a result of the deglaciation. In the modern climate regime, warming of the northern subarctic region results in a northward shift of the jet stream and resultant winter storm tracks, and leads to lower annual precipitation in the southwestern United States [*McCabe*, 1996]. Lake levels and speleothem $\delta^{18}O$ in the southwestern U.S. both suggest drier conditions during the Holocene than the glacial [*Menking et al.*, 2004; *Rasmussen et al.*, 2006; *Oster et al.*, 2009; *Asmerom et al.*, 2010]. Similarly, pollen assemblages from nearby Santa Barbara Basin indicate that the deglaciation was characterized by a shift from cooler, wetter conditions of the glacial interval to the warm, more arid conditions of the Holocene [*Heusser*, 1998]. *Asmerom et al.* [2010] postulate that the jet stream and Pacific Intertropical Convergence Zone shifted rapidly northward during millennial and orbital scale warm episodes of the past 60 kyr, leading to abrupt precipitation changes in southwestern North America, which are consistent with our observations of SST and salinity changes on the California Margin. Similarly, recent model results indicate that a reduction of the Atlantic-Pacific moisture transport during glacial weakening of Atlantic Meridional Overturning Circulation resulted in a southward shift of the Pacific Intertropical Convergence Zone [*Okazaki et al.*, 2010] and movement of precipitation zones south, with the converse taking place during on the deglaciation. Overall, our data indicate that California margin SST and SSS responded similarly on orbital and millennial time scales, as ocean and atmospheric circulation responded to temperature changes in the high northern latitudes.

5. Conclusions

[31] A record of *G. bulloides* Mg/Ca from ODP Site 1017E reveals the history of surface water temperature changes over the past 60 kyr within the context of

hydrographic variability on the California Margin. The Mg/Ca temperature record reveals that in the northeast Pacific, far removed from the direct effects of Northern Hemisphere ice sheets, the last glacial episode was marked by millennial-scale temperature oscillations of $\sim$4–5°C in magnitude. These oscillations are synchronous with previously described Dansgaard-Oeschger type oscillations in δ^{18}O. The δ^{18}O-water record indicates that the oscillations were accompanied by hydrographic changes, such that there was a greater influence of the cold, fresh California Current during stadials and a greater influence of poleward-flowing, warm saline subtropical Countercurrent water during interstadials.

[32] The deglacial SST change on the California Margin was large and rapid, comprising a 5.8 ± 1.6°C warming that began at 16.5 ± 0.5 kyr and that lasted $\sim$1.1 kyr. The large deglacial warming event was preceded by a pre-Bølling warm-cold oscillation of 2.6 ± 1.2°C between 18 and 16.5 kyr. Mg/Ca and δ^{18}O results indicate that deglacial warming preceded the decrease in δ^{18}O by $\sim$1.5 kyr, in contrast to alkenone-based temperature records which indicate a much earlier and smaller warming beginning at $\sim$30 kyr. These results suggest that the California Current remained relatively strong on the Southern California margin until approximately 18 kyr, after which it became reduced in strength relative to the Countercurrent.

[33] Millennial and orbital changes in ocean circulation on the California margin were likely coupled with changes in atmospheric circulation as the polar jet stream shifted southward during stadial and glacial episodes. SSS data from Site 1017 support previous evidence for a southward shift of winter storm tracks during cold episodes, leading to higher precipitation on the California margin during stadials. These results suggest a tight coupling between the North Atlantic and northeast Pacific response to climate instability of the last glacial episode.

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