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Intensification of the northeast Pacific oxygen minimum zone during the Bölling-Alleröd warm period

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Abstract. Although climate records from several locations around the world show nearly synchronous and abrupt changes, the nature of the inferred teleconnection is still poorly understood. On the basis of preserved laminations and molybdenum enrichments in open margin sediments we demonstrate that the oxygen content of northeast Pacific waters at 800 m depth during the Bölling-Alleröd warm period (15-13 kyr) was greatly reduced. Existing oxygen isotopic records of benthic and planktonic foraminifera suggest that this was probably due to suppressed ventilation at higher latitudes of the North Pacific. Comparison with ventilation records for the North Atlantic indicates an antiphased pattern of convection relative to the North Pacific over the past 22 kyr, perhaps due to variations in water vapor transport across Central America.

1. Introduction

For many regions of the globe it is now clear that the transition to modern climate following the Last Glacial Maximum (LGM) was punctuated by a number of rapid and substantial climate oscillations [*Fairbanks*, 1990; *Alley et al.*, 1993]. The Bölling-Alleröd (BA) period of early warming (between 14.7 and 12.9 kyr; ~ 12.5-11.1 kyr ^{14}C years) and a temporary return to coolness during the Younger Dryas (YD) (between 12.9 and 11.6 kyr; ~ 11.1-10.1 kyr ^{14}C years), as dated in Greenland ice cores [*Alley et al.*, 1993], appear to be linked to climate-related changes observed in many marine and continental records [*Fairbanks*, 1990; *Peteet and Mann*, 1994; *Kallel et al.*, 1988]. Well-dated cores show that the BA and the YD correlate with changes in the oxygen content of bottom water in the Gulf of California [*Keigwin*, 1987] and the Santa Barbara basin [*Kennett and Ingram*, 1995], both semienclosed basins in the northeast Pacific, although the exact mechanism linking these rapid transitions on a global scale remains enigmatic. We contribute to this question by showing that low oxygenation of the Gulf of California and Santa Barbara basin during the BA was caused by an abrupt reduction in the oxygen content of open northeast Pacific water at 800 m depth. We further show that the reduction in ventilation was associated with increased stratification of tl upper water column at high latitudes of the North Pacif Ocean.

The oxygenminimum zone (OMZ), typically located in tl 500-800 m depth range, is a characteristic feature of much the global ocean, although its intensity varies widely from o location to another. The shape and intensity of the OM reflects a balance between oxygen consumption by decayi plankton matter as it sinks from the surface and mixes wi oxygenated subsurface water produced at high latitudes l cooling [*Wyrtki*, 1962]. The OMZ of the North Pacifi centered approximately at the σ_θ = 27.2 density surface, most pronounced off Mexico (<5 μM) and gradually weake to the north (~15 μM off California) and to the west (~60 μ off Japan) (Figure 1). This pattern is, in part, a function distance from the Sea of Okhotsk and the Gulf of Alas where well-oxygenated North Pacific Intermediate Wa (NPIW, 26.7 $<\sigma_\theta<$ 26.9) is formed [*Talley*, 199 Hydrographic time series data indicate that the intensity of t OMZ off California is delicately balanced today with resp to variations in the relative contributions of low-oxygen wa from the south and high-oxygen water from the north [*Ly and Simpson*, 1987; *Van Scoy and Druffel*, 1993]. Th suggests that the California margin at the depth of the OM should be a sensitive location to reconstruct past changes the processes that regulate the intensity of the OMZ.

2. OMZ Fluctuations in the Northeast Pacific

In this study we use the preservation of fine laminatic and the concentrations of Mo and Cd in the sediment reconstruct past changes in the intensity of the OMZ California since the LGM. Along most continental margin

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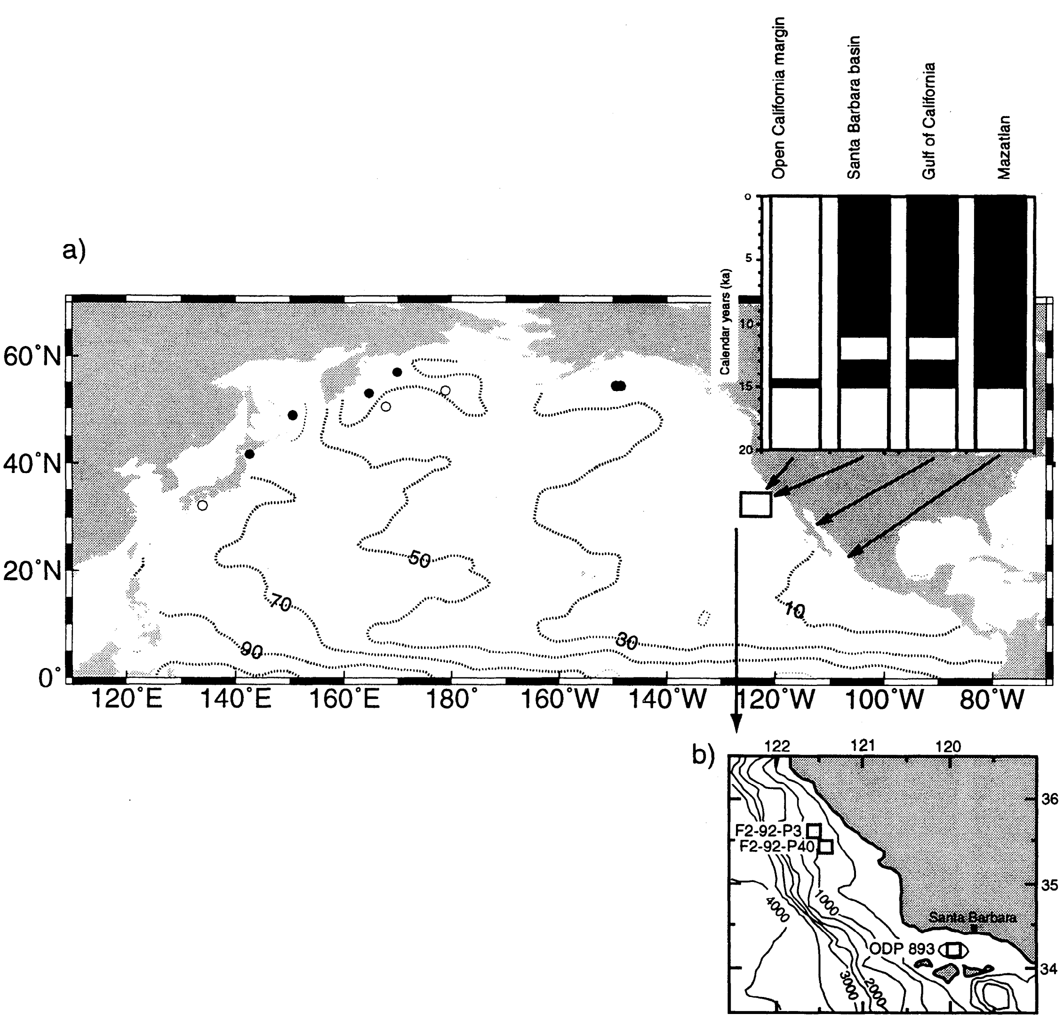

Figure 1. a) Contour map of oxygen concentrations (μM) [*Levitus and Boyer*, 1994] on the σ_θ =27.2 isopycnal surface. This density surface is a good approximation for the location of the OMZ across the North Pacific and increases in depth from 800 to 1000 m from east to west. Large open rectangle indicates enlarged study area on the California margin (Figure 1b). Locations of cores with excess shift in the $\delta^{18}O$ of planktonic foraminifera relative to benthic foraminifera during the Bölling-Alleröd (BA) are indicated by solid circles (CH84-14, RAMA 44PC, core 2594, V34-90, PAR87A-01, PAR87A-02, and PAR87A-10) [*Kallel et al.*, 1988; *Zahn et al.*, 1991; *Keigwin et al.*, 1992; *Gorbarenko*, 1996]. Locations of cores without records of benthic foraminifera but showing a large negative shift in planktonic $\delta^{18}O$ at the onset of the BA are indicated by small open circles [*Gorbarenko*, 1996; *Ohkouchi et al.*, 1994]. Inset of bar graphs shows alternation between laminated (black) and bioturbated sediments (white) over the past 20 kyr at four locations in the northeast Pacific margin: the open California margin [*Gardner et al.*, 1997], the Santa Barbara Basin [*Behl and Kennett*, 1996], the Gulf of California [*Keigwin and Jones*, 1990], and the Mexican margin off Mazatlan [*Ganeshram*, 1996]. Laminated and Mo-enriched surface sediments have been reported at the Mexican margin off Mazatlan as well [*Nameroff*, 1996]. b) Enlarged study area at the California margin where locations of cores F2-92-P3 and F2-92-P40 are indicated (open rectangle, Figure 1a). Location of Ocean Drilling Program Site 893[*Kennett and Ingram*, 1995] in the Santa Barbara basin is also shown.

seasonal cycle modulates the composition of particulate matter reaching the ocean floor. This signature is usually erased by burrowing activities of the benthic macrofauna. Exceptions are anoxic basins such as the Black Sea and the Cariaco Trench as well as areas where bottom water contains < 5 μM oxygen, such as the OMZ off Mexico and the Santa Barbara basin, where bioturbating organisms cannot survive. The preservation of laminations is therefore a clear indication of bottom water oxygen levels < 5 μM. Sedimentary concentrations of Mo and Cd are also sensitive to bottom water oxygen concentrations. Both elements are enriched in marine sediments that accumulate under low-oxygen conditions because of precipitation triggered by a combination of elevated iron and sulfide concentrations in pore waters [*Francois*, 1988; *Shaw et al.*, 1990; *Crusius et al.*, 1996; *Helz et al.*, 1996; *Zheng et al.*, 2000]. In the case of Mo these authigenic enrichments have not been detected in sediment under bottom water oxygen levels >10 μM (Figure 2). This compilation excludes more oxic conditions where Mo can accumulate in sediments above crustal levels in conjunction with Mn oxides [*Shaw et al.*, 1990; *Shimmield and Price*, 1986]. In contrast to Mo, there is no well-defined threshold

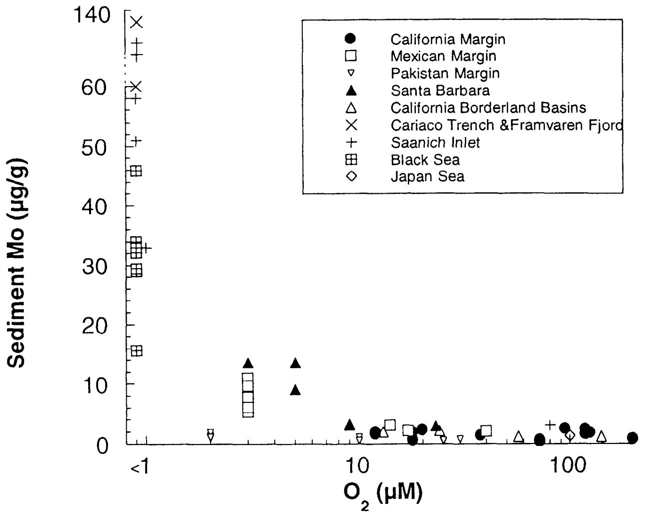

Figure 2. Relation between Mo concentration in modern sediment and bottom water oxygen concentration (California Margin [*Zheng*,1999], Mexican Margin [*Nameroff*, 1996], Pakistan Margin [*Crusius et al.*, 1996], and near shore ocean basins (Saanich Inlet [*Francois*, 1988; *Crusius et al.*,1996], Black Sea [*Crusius et al.*, 1996], Japan Sea [*Crusius et al.*, 1996], Cariaco Trench [*Emerson and Huested*, 1991], Framvaren Fjord [*Emerson and Huested*, 1991], Santa Barbara basin [*Zheng*, 1999] and other California Borderland Basins (Patten Escarpment, San Clemente, Santa Cruz and San Nicholas *Zheng* [1999])). Compilation excludes sediments in which Mo enrichments are believed to be associated with Mn oxyhydroxides [*Shaw et al.*, 1990; *Shimmield and Price*, 1986]. Outlier from Pakistan margin suggests that in addition to low oxygen, a minimum level of organic matter is required to trigger authigenic Mo formation.

oxygen level for authigenic Cd formation because the rain rate of plankton matter reaching the sediment is an important factor in addition to bottom water conditions [*van Geen et al.*, 1995].

Both fine-scale laminations and Mo enrichments are preserved in two piston cores from the continental margin off central California (F2-92-P3 at 35°27.4'N, 121°36.3'W; and F2-92-P40 at 35°25.09'N, 121°24.95'W; 803 and 760 m water depths, respectively; Figure. 1). Radiocarbon-dated planktonic and benthic foraminifera indicate that sedimentation rates in cores P3 and P40 averaged 14 and 25 cm/kyr (Table 1), respectively, over the past 15 kyr [*Gardner et al.*, 1997]. The finely laminated sections preserved between 214 and 204 cm in core P3 and between 372 and 353 cm in core P40 correspond to calendar ages of 14.7-14.4 kyr and 15.0-14.6 kyr, respectively (Figures. 3a and 3b). These intervals are indistinguishable within the accuracy of the age models. Mo concentrations (Table 2) increase in both cores above a detrital background level of ~2 µg/g [*Taylor and McLennan*, 1985] in intervals deposited between 15 and 13 kyr (217-172 cm in core P3, 363-274 cm in core P40, Figures. 3a and 3b). Because threshold oxygen levels for preservation of laminations appear to be lower than that for the precipitation of authigenic Mo [*Zheng*, 1999], we attribute these features to a rapid intensification of the OMZ off California to <5 µ*M* oxygen at the onset of the BA, when Mo was precipitated in laminated sediments, followed by a slight increase to >5 but <10 µ*M* through the duration of the BA, when precipitation of Mo continued but sediments were bioturbated. This suggests a northward expansion of the intense OMZ, characteristic of the Mexican margin today, by at least 10° latitude (1000 km) during the BA (Figure 1). The climax of poor ventilation that occurred during the early BA is consistent with the fluctuation of the oxygen minimum zone intensity based on benthic foraminifera assemblages at ODP site 1017 [*Cannariato and Kennett*, 1999].

Late glacial sediments in the Santa Barbara basin, the Gul of California, and the margins of California and Mexico are bioturbated [*Kennett and Ingram*, 1995; *Keigwin and Jones* 1990; *Ganeshram*, 1996; *Cannariato and Kennett*, 1999] indicating that OMZ waters throughout the region contained sufficient levels of oxygen to sustain populations of benthic macrofauna (Figure 1 inset). Within the uncertainties of the respective age models associated with these four records, the onset of preservation of laminations was synchronous at al sites and coincident with the onset of the BA, indicating an abrupt region-wide intensification of the OMZ associated with a warming climate. Upon return to colder conditions during the YD the OMZ became better ventilated, as indicated by the presence of bioturbated sediments at all sites except the Mexican margin (Figure 1 inset). Intensification of the OMZ coincided again with warming in the Holocene, as suggested by laminated sediments in the Santa Barbara basin and the Gulf of California (Figure 1 inset and Figure 3c). However, a no time during the Holocene did the OMZ off California reach the intensity that existed during the BA for a duration sufficiently long to preserve laminated sediments or Mo enrichments (Figure 1 inset and Figure 3c). Thi interpretation is supported by the variations in the degree o preservation of laminations in Santa Barbara Basin (Figure 3c *Behl and Kennett,* 1996). Preserved laminations and M enrichments reported for other California margin cores sugges that the OMZ may have been as intense as during the BA o several occasions before the LGM [*Dean et al.*, 1997].

3. Causes for Intensification of the OMZ During the BA

What caused the intensification of the OMZ over a larg area of the northeast Pacific during the BA? One possibility i that upwelling-favorable equatorward winds intensifie enhanced productivity, and intensified the OMZ owing t increased oxygen demand associated with regeneration of th products of enhanced productivity. A general circulatio model driven by orbital changes in insolation and melting o the Laurentide ice sheet predicts an increase in equatorwar winds along the North American coast during deglaciatio [*Cooperative Holocene Mapping Project (COHMAP members, 1988*]. However, these changes, qualitative confirmed by productivity proxies measured in cores from th margins of Oregon [*Lyle et al.*, 1992], California [*Gardner al.*, 1997], and Mexico [*Ganeshram*, 1996], were much mo gradual than the synchronized, rapid transition observed at th BA. *Mix et al.* [1999] observed a rapid increase in the organ carbon content of sediments at ODP site 1019 (41.682°N 124.903°W, 980 m water depth) at the onset of the BA, whic they interpreted as an increase in productivity. However, th corresponding changes in our California margin cores a more subdued, with an increase in percent C_{org} from ~ 1.7%

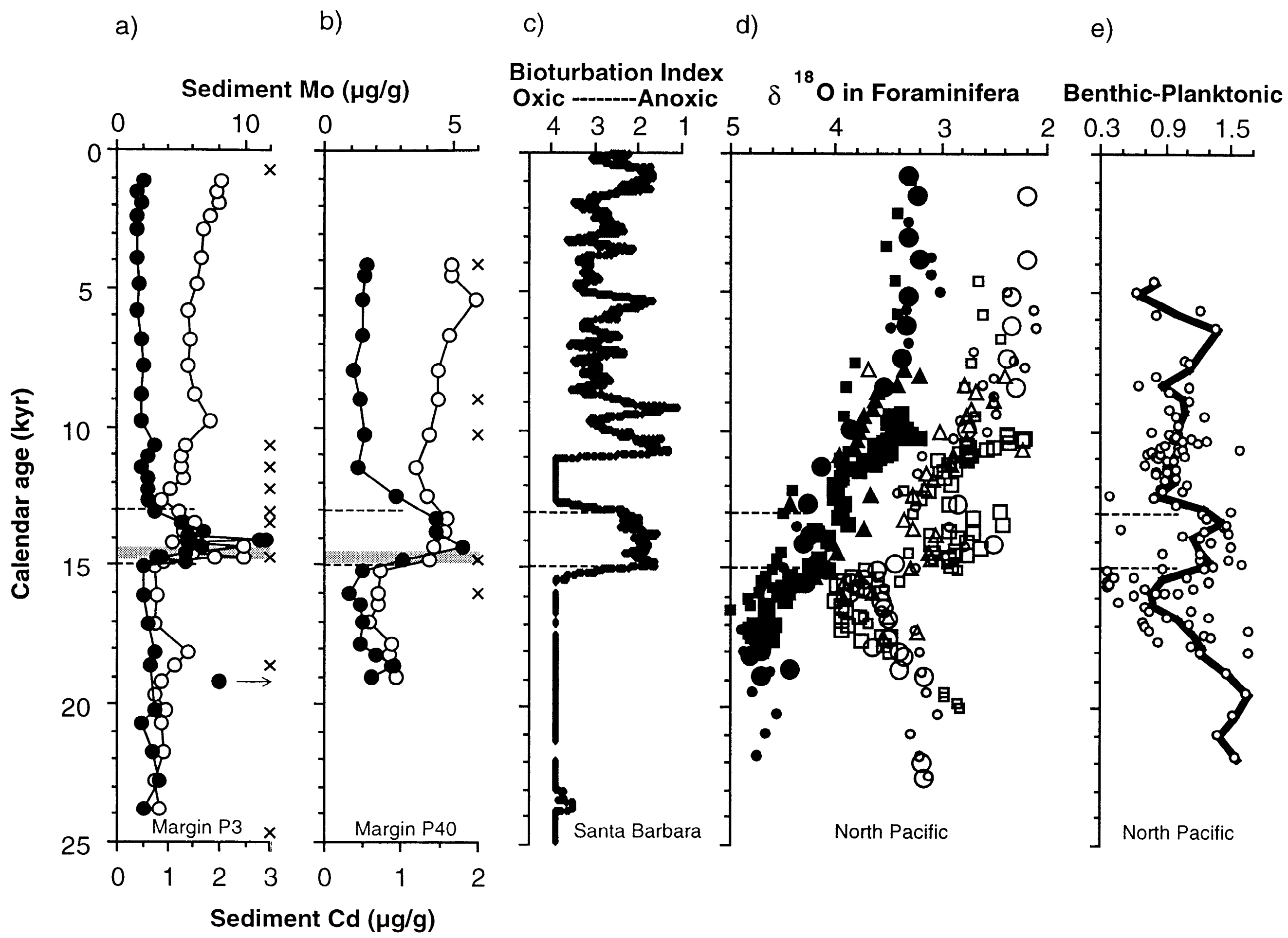

Figure 3. Variations in Mo (solid circle) and Cd (open circle) concentrations in sediments from the California margin at (a) 803 m (F2-92-P3) and (b) 760 m (F2-92-P40) at the depth of the present-day OMZ. Shaded intervals indicate periods of preservation of fine laminations. Crosses indicate calendar ages of accelerator mass sepctrometry ^{14}C-dated foraminifera used to construct aged models for each core [*Gardner et al.*, 1997] combined with new radiocarbon data for P40 (Table 1). Mo and Cd concentrations (Table 2) were measured by isotope-dilution inductively coupled plasma - mass spectrometry following a total acid dissolution of sediment [*Zheng*, 1999]. Detrital background concentrations, Mo of ~2 μg/g and Cd of ~0.1 μg/g, do not vary significantly in either core [*Taylor and McLennan*, 1985]. Horizontal arrow corresponds to Mo determinations (18 and 29 μg/g at 312 cm) that are not associated with any increase in Cd. (c) Smoothed bioturbation index record of Santa Barbara Basin ODP site 893 [*Behl and Kennett*, 1996], with larger values indicating higher degree of oxygenation. (d) Planktonic (open symbols) and benthic (solid symbols) foraminifera δ^{18}O for sites in the far North Pacific (locations are indicated by solid circles in Figure 1): CH84-14 (large square), RAMA 44PC (small square), core 2594 (triangle), V34-90 (small circle), and PAR87A-10 (large circle) [*Kallel et al.*, 1988; *Zahn et al.*, 1991; *Keigwin et al.*, 1992; *Gorbarenko*, 1996]. (e) Composite of difference in δ^{18}O for all paired benthic and planktonic data. The thick line shows the difference between paired benthic and planktonic δ^{18}O measured in the same cores averaged over 500 year intervals.

15 kyr to ~ 2.2% by the end of the BA and with a further gradual increase to 2.7% through the Holocene [*Gardner et al.*, 1997]. While the rise in percent C_{org} during the BA may have been influenced by an increase in productivity, it may also have been a consequence of increased preservation under reduced concentrations of bottom water oxygen. The degree to which organic carbon preservation is regulated by bottom water oxygen has long been debated, but recent studies of OMZ sediments show conclusively that the quality and quantity of C_{org} preserved is sensitive to bottom water oxygen, especially at concentration < 20 μ*M* [*Keil et al.*, 1999; *Paropkari and Keil*, 1999]. Consequently, the increased C_{org} content of BA sediments cannot be used as conclusive evidence for increased productivity.

The authigenic Cd content of sediments is regulated both by bottom water oxygen concentration and by the rain of the particulate organic matter to the seafloor [*van Geen et al.*, 1995]. The maximum Cd concentration in BA sediments is comparable to levels in late Holocene sediments (Figures 3a and3b). Because bottom water oxygen concentrations during the BA were lower than today, as demonstrated by the preserved varves, the comparable Cd concentrations suggest that the rain of C_{org} during the BA may have been lower than today as well. It is difficult to estimate quantitatively changes

Table 1. List of Raw AMS and Conventional ^{14}C Ages and Their Calendar Year Equivalent

Depth in Core, cm	Planktonic Foram	AMS ^{14}C Date Raw ^{14}C Years	 Error of Raw Age	Calendar Years[a]	LLNL Numbers
		Core F2-92-P3			
0	mixed	1770	60	949	
90	mixed	9500	90	10018	5264
100	mixed	9540	90	10063	5265
102	*N. pachyderma*	9430	70	10004	6882
102	*G. bulloides*	9450	80	10034	6883
120	mixed	10020	100	10736	5266
140	mixed	10620	100	11502	5267
160	mixed	11810	110	13008	5268
163	*G. bulloides*	11790	230	12983	6253
170	mixed	12150	140	13436	5276
200	*N. pachyderma*	13020	140	14523	7488
200	*G. bulloides*	12930	140	14411	7489
214	mixed	13140	110	14673	5269
298	mixed	16650	220	18965	5282
400	*N. pachyderma*	19670	400	23797	7491
400	*G. bulloides*	20310	750	23288	7492
440	*N. pachyderma*	20910	270	23982	7494
440	*G. bulloides*	20490	270	23497	7503
470	*N. pachyderma*	22580	350	25891	7504
470	*G. bulloides*	21420	290	24568	7505
570	*N. pachyderma*	25670	570	29336	7506
570	*G. bulloides*	26100	540	29807	7507
		Core F2-92-P40			
140	*N. pachyderma*	8660	60	9060	6260
220	mixed	10310	90	11106	6261
360	mixed	13230	120	14784	6262
410	mixed	13390	120	14983	6269

[a] Calendar years is obtained by correcting a resevoir age of 625 years, followed by calculation using equations (1) (< 9 kyr) and (2) (> 9 kyr) by *Gardner et al*. [1997].

in productivity from changes in sedimentary Cd and percent C_{org}, but it is safe to conclude that productivity at the sites of our cores during the BA was no greater than today, and it may have been less. Therefore one must look to other factors to explain changes in OMZ intensity.

Records of the oxygen isotopic composition of planktonic and benthic foraminifera at five sites distributed across the far North Pacific, including the Gulf of Alaska and the Sea of Okhotsk, indicate changes in high-latitude surface forcing of ventilation during the BA (Figure 1a). The benthic records reflect primarily the release of ^{18}O-depleted meltwater from continental ice sheets during deglaciation. The oxygen isotopic composition of planktonic foraminifera reflects a combination of factors, including the isotopic composition (which is related, in turn, to salinity) [*Craig and Gordon*, 1965; *Zahn et al.*, 1991] and temperature [*O'Neil et al.*, 1969] of the seawater in which calcification occurred. One feature that is common to all paired isotope records is that the difference between the oxygen isotopic composition of benthic and planktonic foraminifera ($\Delta\delta^{18}$O) nearly doubled from 0.7 to 1.3‰ during the BA, with almost all the changes associated with planktonic δ^{18}O (~ 1.4‰; Figures. 3d and 3e). If the modern salinity and δ^{18}O relationship held at 15 kyr, then the 0.6‰ increase in $\Delta\delta^{18}$O during the BA could be explained either by ~ 1‰ reduction in surface salinity or by surface warming of 2.5°C, or some combination thereof. The corresponding decrease in density is larger for a 1‰ salinity change (~0.8 unit) than for a 2.5°C temperature change (0.2-0.4 units, depending on the initial temperature). The isotopic evidence for reduced surface water density during the BA is clear in all regions where NPIW forms today or could potentially have formed in the past. Because the intensity of the OMZ of the subtropical northeast Pacific is modulated by changes in ventilation at higher latitudes today, we conclude that the OMZ was particularly intense during the BA because of increased stratification at high latitudes.

What process enhanced the stratification of the high-latitude North Pacific during the BA? A number o mechanisms, such as input of glacial meltwater and enhanced precipitation during the BA, have been proposed to explain an apparent reduction in surface water salinity in the region [*Keigwin et al.*, 1992; *Gorbarenko*, 1996]. Warmer and moister climate during the BA indicated by vegetation changes on Kodiak Island, Alaska, suggest that both temperature and salinity may have played a role [*Peteet and Mann*, 1994]. We believe, however, that tropical forcing

Table 2. Concentrations of Cd, Mo, U, and Th in Piston Cores at 35°N California Margin

Depth, cm	Calendar Age kyr[a]	Mo, μg/g	σMo[b]	Cd, μg/g	σCd[b]	U, μg/g	σU[b]	Th, μg/g	σTh[b]
		F2-92-P3		*(35.6232 °N, 121.6222 °W,*		*786 m)*			
TW5	0.78	1.64	0.24	1.88	0.01	4.78	0.05	10.11	0.05
TW15	1.66	1.90	0.11	1.63	0.03	4.01	0.02	9.33	0.12
TW25	2.57	1.72	0.09	1.98	0.01	3.90	0.01	9.36	0.03
TW35	3.44	1.77	0.31	1.88	0.01	4.36	0.04	9.57	0.04
TW45	4.31	1.69	0.11	1.89	0.01	4.46	0.01	9.82	0.05
4	1.10	2.01	0.10	2.03	0.00	5.18	0.03	9.97	0.10
8	1.49	1.58	0.03	1.97	0.02	5.51	0.05	9.95	0.10
12	1.89	1.91	0.08	2.02	0.04	4.96	0.00	10.20	0.06
17	2.38	1.55	0.17	1.82	0.01	5.00	0.04	9.27	0.07
22	2.88	1.57	0.17	1.71	0.01	4.89	0.01	10.72	0.07
32	3.87	1.54	0.18	1.67	0.00	4.97	0.02	10.28	0.09
42	4.85	1.75	0.02	1.56	0.00	4.82	0.00	10.17	0.01
52	5.84	1.56	0.59	1.37	0.02	4.74	0.06	10.31	0.10
62	6.83	1.94	0.29	1.45	0.02	4.62	0.03	9.80	0.07
72	7.82	2.14	0.04	1.41	0.03	4.96	0.01	10.24	0.05
82	8.81	1.91	0.08	1.52	0.01	4.91	0.06	10.26	0.02
92	9.80	1.90	0.06	1.82	0.01	4.72	0.05	9.80	0.08
102	10.67	2.87	0.25	1.35	0.00	4.85	0.04	10.19	0.12
112	11.07	2.50	0.05	1.28	0.00	4.70	0.04	9.88	0.11
122	11.47	1.90	0.21	1.24	0.02	4.67	0.03	10.00	0.09
132	11.88	2.38	0.14	1.29	0.01	4.34	0.01	10.05	0.10
142	12.28	2.36	0.11	1.05	0.02	4.49	0.05	9.93	0.10
152	12.69	2.44	0.00	0.87	0.00	4.16	0.00	9.66	0.08
162	13.09	2.89	0.12	1.20	0.01	5.04	0.05	10.54	0.10
172	13.49	4.98	0.25	1.51	0.02	5.81	0.02	9.94	0.01
182	13.77	6.71	0.40	1.31	0.00	5.28	0.08	9.75	0.02
187	13.91	5.48	0.37	1.52	0.00	5.51	0.01	10.25	0.01
192	14.05	11.72	3.09	1.41	0.01	5.11	0.02	9.33	0.12
192	14.05	11.10	1.08	1.43	0.01	5.25	0.04	8.97	0.08
197	14.19	5.48	0.10	1.09	0.00	5.10	0.04	9.53	0.05
202	14.36	6.60	0.97	2.47	0.01	5.93	0.10	8.66	0.13
207	14.53	5.42	0.60	1.47	0.02	5.32	0.04	9.86	0.13
212	14.70	3.51	0.21	1.93	0.03	5.49	0.03	9.86	0.06
212	14.70	3.13	0.36	2.48	0.05	5.27	0.04	9.21	0.06
217	14.88	5.33	0.54	0.93	0.01	4.28	0.02	8.75	0.14
222	15.08	2.03	0.11	0.72	0.01	4.15	0.03	9.09	0.07
242	16.10	2.08	0.40	0.78	0.00	4.66	0.04	9.17	0.13
262	17.13	2.51	0.55	0.73	0.04	3.59	0.06	8.69	0.06
282	18.15	2.99	0.26	1.39	0.01	5.34	0.01	9.67	0.06
292	18.66	2.57	0.00	1.15	0.02	4.67	0.02	9.52	0.08
302	19.17	7.95	0.04	0.87	0.02	4.89	0.03	7.82	0.05
312	19.68	23.47	0.45	0.76	0.02	5.15	0.02	9.26	0.02
322	20.19	2.90	0.06	0.94	0.02	4.48	0.04	7.96	0.18
332	20.70	1.92	0.17	0.85	0.06	4.03	0.01	8.82	0.05
352	21.72	2.72	0.16	0.93	0.03	4.62	0.01	9.19	0.01
372	22.75	3.39	0.37	0.72	0.00	4.78	0.02	8.97	0.00
392	23.77	2.15	0.38	0.84	0.00	3.88	0.01	8.82	0.06

ultimately needs to be invoked in order to explain (1) the remarkable synchroneity between rapid climate change in the North Atlantic and the North Pacific regions over the course of deglaciation and (2) the antiphased pattern of changes in thermohaline circulation (THC) of the North Atlantic and North Pacific Oceans, whereby ventilation of the North Atlantic shoaled during the LGM and YD as it deepened in the North Pacific and vice versa during the BA and Holocene [*Kroon et al.*, 1997; *Mikolajewicz et al.*, 1997; *Lund and Mix*, 1998; *Marchitto et al.*, 1998].

Table 2. (continued)

Depth, cm	Calendar Age kyr[a]	Mo, µg/g	σ Mo[b]	Cd, µg/g	σ Cd[b]	U, µg/g	σ U[b]	Th, µg/g	σ Th[b]
		F2-92-P40		*(35.4182 ° N, 121.4158 ° W, 760 m)*					
1	4.14	1.64	0.20	1.66	0.01	4.18	0.05	7.70	0.10
12.5	4.50	1.56	0.02	1.65	0.03	3.94	0.04	10.33	0.15
42	5.44	1.44	0.20	1.96	0.03	4.30	0.02	9.34	0.05
82	6.71	1.47	0.06	1.61	0.04	4.35	0.05	7.78	0.02
122	7.99	1.13	0.08	1.48	0.02	3.81	0.02	8.31	0.04
154	9.01	1.40	0.07	1.48	0.01	4.28	0.05	8.08	0.10
194	10.28	1.59	0.10	1.37	0.00	3.90	0.01	7.75	0.07
234	11.47	1.32	0.02	1.19	0.04	3.65	0.02	7.77	0.04
274	12.52	2.77	0.00	1.32	0.00	4.52	0.02	8.15	0.02
303	13.29	4.33	0.05	1.58	0.03	3.90	0.01	7.98	0.09
323	13.81	4.38	0.46	1.57	0.07	4.19	0.02	8.11	0.00
343	14.34	5.38	0.27	1.41	0.00	4.45	0.05	8.27	0.06
363	14.84	3.04	0.25	1.36	0.01	4.20	0.01	7.86	0.00
383	15.24	1.52	0.25	0.71	0.01	4.13	0.00	7.31	0.01
423	16.03	1.00	0.09	0.69	0.01	4.31	0.03	6.83	0.04
443	16.43	1.35	0.16	0.70	0.01	4.12	0.00	7.34	0.01
473	17.02	1.44	0.03	0.57	0.01	3.69	0.00	7.60	0.04
513	17.82	1.42	0.35	0.86	0.04	4.06	0.00	6.85	0.02
533	18.21	1.98	0.02	0.83	0.06	3.85	0.01	8.02	0.09
553	18.61	2.70	0.08	0.87	0.00	4.18	0.05	8.21	0.10
573	19.01	1.83	0.03	0.91	0.01	3.67	0.02	8.29	0.05

[a] Age model (Table 1) obtained following the method described by *Gardner et al.* [1997].

[b] Here σ indicates 1 σ analytical error of Mo, Cd, U, and Th cocentrations.

Specifically, we propose that variations in the transport of water vapor from the tropical Atlantic Ocean to the Pacific Ocean controlled the inverse pattern of ventilation depth of the North Atlantic and the North Pacific Oceans since the LGM. The greater density of deep water formed at high latitude in the North Atlantic, compared to the Pacific, is maintained, in part, by excess evaporation in the North Atlantic and transport of water vapor across Central America to the Pacific by the trade winds [*Broecker et al.*, 1990]. The relation between water vapor transport and sea surface temperature (SST) is complex [*Clement and Seager*, 1999]. However, if we can assume that wind speed and relative humidity did not vary significantly in the tropical North Atlantic over the course of deglaciation, the change in evaporative flux from the region becomes primarily a function of SST. Coral records suggest that tropical Atlantic SST increased by several degrees during the transitions from LGM to BA and from YD to Holocene [*Guilderson et al.*, 1994]. If tropical Atlantic SST increased from 20° to 25°C, for example, then this would translate into an increase of ~40% in evaporation according to the Clausius-Clapeyron equation and, presumably, into an increase in the transport of water vapor from the Atlantic to the Pacific. Increased water vapor transport across Central America would have reduced the salinity and therefore the density of surface waters advected to high latitudes of the North Pacific while increasing surface salinities in the North Atlantic. Because excess evaporation in the North Atlantic determines the overall nature and rate of deep water formation at high northern latitudes today [*Weyl*, 1968], it is plausible that changes in the flux of water vapor transported from the North Atlantic to the North Pacific determined the inverse pattern of ventilation depth in the two basins during climatic fluctuations associated with the transition from the LGM to the Holocene.

Modern observations support the notion of antiphased ventilation of the two ocean basins on relatively short timescales. Repeated hydrographic transects across the North Pacific Ocean have detected a distinct freshening of North Pacific Intermediate Waters in recent decades, attributed to increased precipitation (minus evaporation) at high latitudes [*Wong et al.*, 1999]. Contemporary cruises in the North Atlantic Ocean, on the other hand, have identified a steady increase in salinity of the main thermocline and intermediate waters [*Bryden et al.*, 1996]. It therefore appears that a mechanism similar to that invoked to explain changes in ventilation of intermediate waters during climatic fluctuations associated with the transition from the LGM to the Holocene may operate on shorter timescales as well.

Why was ventilation in the North Pacific more subdued during the BA than during the Holocene? Convection in the North Atlantic was also greater during the BA than at any time since the LGM [*Marchitto et al.*, 1998], leading some [*Kroon et al.*, 1997] to characterize ocean thermohaline circulation at that time as operating in a "super conveyor mode. Varying the flux of water vapor across Central Americ provides a mechanism to explain not only the tempora component of antiphase behavior of high-latitude convection but also the intensity of convection. Early warming in th North Atlantic or some other as yet unidentified condition may have generated a flux of water vapor across Central America during the BA that has been unequaled anytime sinc then, creating both the super conveyor in the North Atlantic and restricting severely ventilation in the North Pacific.

Consequences for ocean thermohaline circulation and for global climate of varying the flux of water vapor across Central America have long been appreciated; for example, *Weyl* [1968] suggested that a reduction of this flux could initiate an ice age by reducing the formation rate of North Atlantic Deep Water (NADW). While we are unaware of efforts to model the consequences of enhanced water vapor flux, as we propose for the BA, recent modeling of the converse effect, involving a net transfer of freshwater from the tropical Pacific to the tropical Atlantic, demonstrated the potential breakdown of NADW formation and the formation of a new convection cell in the North Pacific [*Rahmstorf*, 1995]. Our reconstruction further illustrates the important linkages between tropical SST, atmospheric water vapor transport, and ocean thermohaline circulation and provides a mechanism to explain the basin-scale antiphase behavior of ventilation in the North Atlantic and North Pacific Oceans.

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