Equatorward shift of the subarctic boundary in the northwestern Pacific during the last deglaciation

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[1] We have generated a high-resolution record of alkenone sea surface temperature (SST) between 10–24 ka from Core MD01-2421 off central Japan, in the northwestern Pacific. The cooling by 5°C from 21 ka to 12.8 ka implies the equatorward shift of the subarctic boundary in the northwestern Pacific by ~2.8° in latitude. This shift was a result of the stronger summer Okhotsk High. The Okhotsk High was likely enhanced by the combined effects of El Niño-like conditions in the tropical Pacific and the heating of the land surface of northeastern Siberia. **Citation:** Yamamoto, M., R. Suemune, and T. Oba (2005), Equatorward shift of the subarctic boundary in the northwestern Pacific during the last deglaciation, *Geophys. Res. Lett.*, *32*, L05609, doi:10.1029/2004GL021903.

1. Introduction

[2] The last glacial period ended with the last deglaciation. The deglaciation process involves global warming, the increase of greenhouse gases such as carbon dioxide and methane, and the rising of the sea level. The onset of sea surface warming varied in different regions (in the Pacific, reviewed by *Kiefer and Kienast* [2005]). The earliest warming occurred in the California Borderland before 20 ka [*Herbert et al.*, 2001]. The southern hemisphere oceans, the eastern tropical Pacific, the eastern tropical Atlantic and the Antarctic ice cores showed an onset of gradual warming at ~20 ka [e.g., *Lea et al.*, 2000; *Petit et al.*, 1999]. The North Atlantic, the Caribbean Sea, the South China Sea, the East China Sea and the Greenland ice cores showed an abrupt two-step warming at ~14.7 ka and ~11.6 ka with a cold interval in the Younger Dryas period [e.g., *Stuiver et al.*, 1997]. The mid-latitude northwestern Pacific showed an abrupt warming at 11–12 ka [e.g., *Oba and Murayama*, 2004]. These variations presumably resulted from the mechanisms of warming. Establishing more detailed features of deglacial warming in different regions may help us to understand the mechanisms of deglacial warming.

[3] The mid-latitude northwestern Pacific is one of the region of the globe where deglacial warming occurred latest at Termination I [e.g., *Oba and Murayama*, 2004; *Yamamoto et al.*, 2004]. The region contains the subarctic boundary between the subtropical Kuroshio and subarctic Oyashio Currents (Figure 1). Early studies roughly reconstructed that the subarctic boundary shifted southward during the last glacial period and northward during the last interglacial period [e.g., *Moore et al.*, 1980; *Thompson and Shackleton*, 1980]. *Chinzei et al.* [1987] demonstrated a northward displacement of the Kuroshio Front from 16.2 ka to 7.5 ka. They also reported a Younger Dryas-type cooling at 11.9 ka. A pollen study demonstrated the southward expansion of open taiga vegetation on the Hokkaido Island between 13.2–14.0 ka [*Igarashi*, 1996].

[4] We have generated a high-resolution record of alkenone sea surface temperature (SST) between 10–24 ka from Core MD01-2421 taken off the coast of central Japan, the northwestern Pacific. This study aims at examining the latitudinal shift of the subarctic boundary of the northwestern Pacific during the last deglaciation period on centennial and millennial time scales in order to understand why the deglacial warming was late and abrupt in the northwestern Pacific compared to other regions. The site (36°N) is located in the mixing zone (35°N–40°N at present) of warm Kuroshio and cold Oyashio waters. The high sedimentation rate (average 26 cm/ky) between 10–24 ka allows us to perform much higher resolution analysis than in the previous studies.

2. Materials and Methods

[5] A piston core MD01-2421 (45.82 m long) was collected from off the coast of central Japan at 36°02′N, 141°47′E, and a 2224-meter water depth during IMAGES VII-WEPAMA Leg 2 in 2001 [*Oba and Murayama*, 2004] (Figure 1). The age model was presented by *Oba and Murayama* [2004].

[6] A total of 64 samples were collected from the horizon 6–11 m deep (10.0–24.0 ka) in the core. High-resolution analysis was conducted between 10.7 ka and 12.0 ka with the interval of 2.5 cm (~56 years), and the analysis of the horizon between 12.0 ka and 24.0 ka was done basically every 7.5 cm (~300 years). The analysis of alkenones and the calculation of temperature were conducted following the methods of *Yamamoto et al.* [2000] and *Prahl et al.* [1988], respectively, with an analytical accuracy of 0.24°C.

3. Results and Discussion

3.1. Paleo-SST Record From Core MD01-2421 During 10,000–24,000 Years Ago

[7] SST varied between 12.9° and 19.9°C between 10–24 ka (Figure 2b). The SST in the last glacial maximum centered at 21 ka was ~18°C, which is only 1°C lower than the present annual mean SST (19°C) at the studied site [*Japan Oceanographic Data Center*, 1995]. The SST decreased to ~15°C from 21 to 15 ka with a high fluctuation of ~2°C in amplitude. After 14.7 ka, the SST increased by ~1°C and was almost constant at ~16°C during 1 kyr, which correlates with the North Atlantic Bølling-Allerød warm

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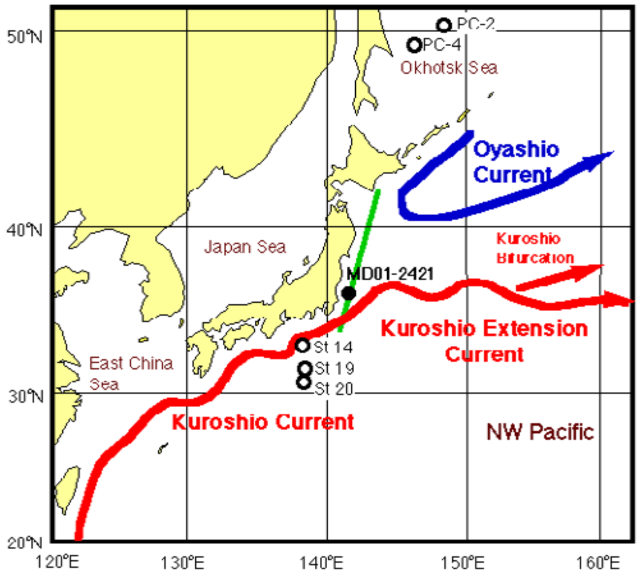

Figure 1. Map showing the locations of Core MD01-2421 and the sites of previous studies. The latitudinal gradient of sea surface temperature (SST) in June was obtained from 30-year average SST along the green line in the figure [*Japan Oceanographic Data Center*, 1995].

period. The SST subsequently decreased and reached ~13°C between 13.2–12.3 ka, which correlates with the North Atlantic Younger Dryas cold period. The SST abruptly increased from ~13°C to ~20°C during the next 1.5 kyr from 12.3 ka to 10.8 ka. The averaged rate of SST increase was ~4.7°C/kyr. The SST increase was not monotonous, but was accompanied with centennial-scale variability of ~1°C amplitude (Figure 2d).

3.2. Latitudinal Displacement of the Northwestern Pacific Subarctic Boundary

[8] As shown in Figure 2b, the variation of SST in Core MD01-2421 between 10–24 ka (7.0°C) was much larger than those in the Okhotsk Sea (2.3°C and 3.5°C in Cores PC2 and PC4, respectively) [*Seki et al.*, 2004] and in Izu Ridge (3.2°C, 2.2°C and 0.9°C in Cores St 14, St 19 and St. 20, respectively) [*Sawada and Handa*, 1998]. The large SST variation in Core MD01-2421 compared to the subtropical and subarctic regions is attributed to the latitudinal displacement of the subarctic boundary.

[9] By assuming that the SST records from St 19 and St 20 at Izu Ridge [*Sawada and Handa*, 1998] represent the changes of SST in the subtropical northwestern Pacific, we evaluated the SST variation caused by the latitudinal displacement of the subarctic boundary. ΔSST_{NWP} was obtained by subtracting the averaged SST of Core St 19 and St 20 [*Sawada and Handa*, 1998] from the SST of Core MD01-2421. The ΔSST_{NWP} ranged from −8.0°C to −2.1°C during the 10–24 ka period (Figure 2c). The core-top ΔSST_{NWP} was −5.3°C. The main path of the Kuroshio is located at 35°N near the studied site. At 12.8 ka, ΔSST_{NWP} was −8.0°C, which is 2.3°C lower than the core-top value. Since the latitudinal gradient of SST in the Kurosio-Oyashio transition zone is ~1.64°C per latitudinal degree along the Japan margin (Figure 1) [*Japan Oceanographic Data Center*, 1995], the 2.3°C drop of ΔSST_{NWP} at 12.8 ka implies the southward shift of the Kuroshio Current by ~1.4° relative to today and its latitudinal position at ~33.6°N. At 10.4 ka, ΔSST_{NWP} was −2.1°C, which is 3.2°C higher than the core-top value, implying the northward shift of the Kuroshio Current by ~2.0° and its latitudinal position at ~37.0°N. In analogy, the 4.6°C drop of ΔSST_{NWP} from 21 ka to

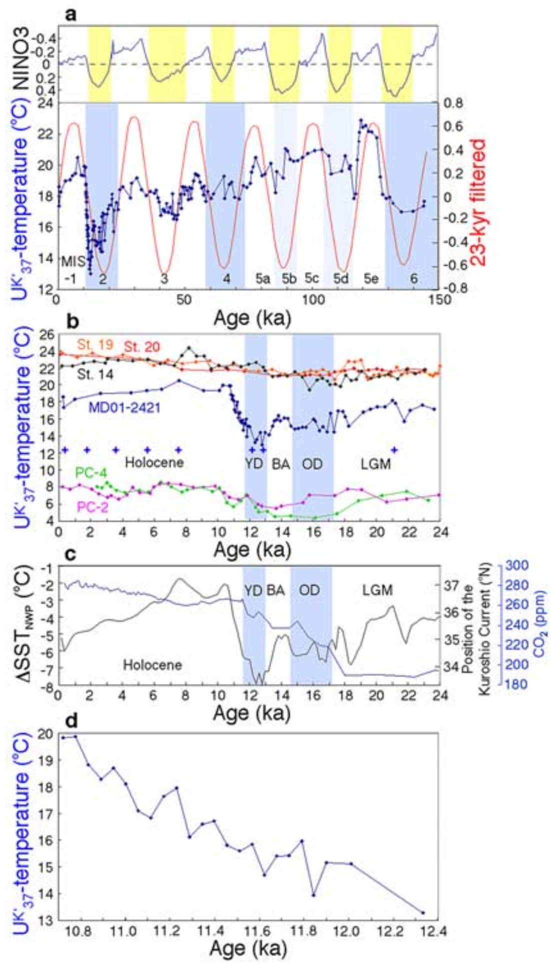

Figure 2. Paleo-SST records on different time scales from Core MD01-2421. (a) Low-resolution record of the last 145 kyr [*Yamamoto et al.*, 2004; this study] with the 23-kyr bandpass-filtered variation of SST and predicted NINO3 index [*Clement et al.*, 1999]. (b) Record of SST during the last 24 kyr with the paleo-SSTs in the Okhotsk Sea (Cores PC2 and PC4) [*Seki et al.*, 2004] and at Izu Ridge, northwestern Pacific (Cores St 14, St 19 and St 20) [*Sawada and Handa*, 1998]. (c) The paleo-SST difference between Core MD01-2421 and Cores St 19 and St 20 with the variation of atmospheric carbon dioxide concentration (CO_2) [*Indermühle et al.*, 1999; *Smith et al.*, 1999]. (d) High-resolution record of SST from 12,300 to 10,700 years ago. YD: Younger Dryas, BA: Bølling-Allerød, OD: Oldest Dryas, LGM: Last Glacial Maximum. +: C-14 dates of mixed planktonic foraminifera *Neogloboquadrina dutertrei* and *Globorotalia inflata* used for age models [*Oba and Murayama*, 2004].

12.8 ka implies the southward shift of the Kuroshio Current by ∼2.8° in latitude.

3.3. Modern Climatic Factors Controlling the Latitudinal Position of the Northwestern Pacific Subarctic Boundary

[10] A time series sediment-trap study demonstrated that alkenone temperature reflects early summer SST at this site [*Sawada et al.*, 1998]. The latitudinal position of the subarctic boundary associated with the westerly jet in early summer is principally controlled by the relative intensities of the Okhotsk High and the North Pacific High. When the Okhotsk High is stronger, the northward shift of the westerly jet is delayed in early summer. The Okhotsk High is enhanced both in an El Niño event [e.g., *Nitta*, 1987] and the positive phase of the North Atlantic Oscillation (NAO) [*Ogi et al.*, 2004] through atmospheric teleconnections.

[11] The depressed North Pacific High and the strengthened Okhotsk High in the summer of El Niño years tend to delay the northward shifts of the westerly jet and oceanic subarctic boundary [*Goes et al.*, 2001], cooling the Japan margin [*Nitta*, 1987; *Kawamura et al.*, 1998]. In La Niña years, the tropical convection center moves to the western equatorial Pacific. It excites the Pacific-Japan teleconnection pattern in summer [*Nitta*, 1987] and accelerates the northward shift of the subarctic boundary, warming the Japan margin [*Nitta*, 1987; *Kawamura et al.*, 1998]. These modern observations suggest that tropical ENSO-like variability has exerted an influence on the mid-latitude northwestern Pacific. An SST record in July from 1974 to 2003 in the Nakaminato harbor (36°21′N, 140°37′E) near the site of Core MD01-2421 showed that the SST was 0.3°C lower in El Niño years and 0.4°C higher in La Niña years than 30-year average (Ibaraki Prefecture, unpublished data, 2004, available at http://host.agri.pref.ibaraki.jp/~suishi/temp.htm).

3.4. Equatorward Displacement of the Northwestern Pacific Subarctic Boundary During the Last Deglaciation

[12] Spectral analysis of alkenone SST indicates that the variation during the last 145 kyr is pronounced at 23 kyr (precession), 30 kyr (also found in equatorial Indo-Pacific paleoproductivity records [*Beaufort et al.*, 2001]) and 100 kyr (eccentricity) periods [*Yamamoto et al.*, 2004]. Recently, *Beaufort et al.* [2001] showed that variations in equatorial productivity have reflected precession-controlled changes in the east-west thermocline slope of the Indo-Pacific, which agreed with the model prediction of long-term variation of El Niño-Southern Oscillation (ENSO) [*Clement et al.*, 1999]. *Yamamoto et al.* [2004] showed a precession-controlled east-west seesaw-like change of alkenone SST in mid-latitude North Pacific margins, which was attributed mainly to the effect of orbital-scale changes in the ENSO behavior through atmospheric teleconnections. The warmer periods, such as the MIS-2/3 and -3/4 boundaries, correspond to the periods when the tropical Pacific was in a La Niña-like condition [*Clement et al.*, 1999] (Figure 2a). This correspondence suggests a strong linkage between the latitudinal displacement of the Kuroshio-Oyashio transition zone and the climatic condition of the tropical Pacific.

[13] Although the orbital-scale anti-phase SST variation in mid-latitude North Pacific margins was a main result of the long-term ENSO-like variability, extreme conditions (ENSO-like SST pattern in the North Pacific observed during strong El Niño) appeared during the last two deglaciations [*Yamamoto et al.*, 2004]. This extreme condition is attributed to the strong cooling in the Kuroshio-Oyashio transition zone during deglaciations, and the cooling was significant mainly in the transition zone (Figure 2b). El Niño-like conditions prevailed within those periods in the tropical Pacific, but the extent was not significant compared with other El Niño-like periods such as late MIS-4, MIS-5b and MIS-5d [*Clement et al.*, 1999; *Beaufort et al.*, 2001]. This mismatch suggests that the strong cooling of the northwestern Pacific in this period cannot be attributed to long-term ENSO-like variability alone, but to other climate-driving processes.

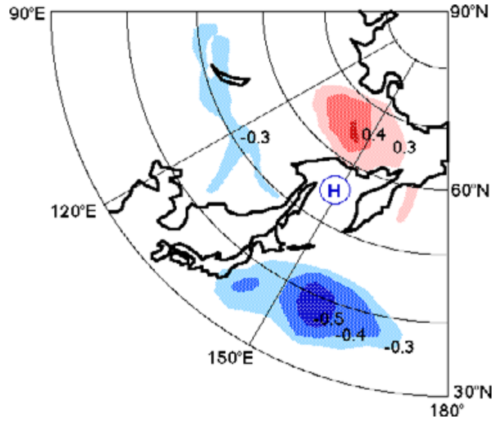

Figure 3. The correlation coefficients between the Okhotsk High index (50°–60°N, 140°–160°E) in June and the surface temperature at 2-m and sea surface temperature in June (modified from *Ogi et al.* [2004]). The "H" in the figure indicates the mean position of the Okhotsk High.

[14] A recent meteorological study indicated that the summer Okhotsk High is enhanced by the summer heating of northeastern Siberia, north of the Okhotsk Sea [*Ogi et al.*, 2004]. The strong Okhotsk High is associated with warmer surface temperatures to the north and cooler temperatures to the south (Figure 3). The warm air-temperature anomalies in northeastern Siberia make a preferable condition for upper-level blocking, which is usually accompanied by the Okhotsk High [*Ogi et al.*, 2004]. The northerly cold air advection to the south of the Okhotsk High generates cold SST anomalies in the Kuroshio-Oyashio transition [*Ogi et al.*, 2004].

[15] The insolation in June at 65°N, where the center of the positive temperature anomaly is located when the Okhotsk High is strengthened [*Ogi et al.*, 2004], was maximized at 11 ka [*Berger*, 1978]. The enhanced heating of the land surface due to increasing insolation might have resulted in the stronger summer Okhotsk High during the latter stage of the last deglaciation. More likely, the increase of greenhouse gasses might have resulted in the strengthened Okhotsk High. Carbon dioxide concentration increased during the last deglaciation [*Indermühle et al.*, 1999; *Smith et al.*, 1999] (Figure 2c). AOGCM CO_2 sensitivity tests (reviewed by *Intergovernmental Panel on Climate Change* [2000]) indicated the "Polar amplification" that the warm-

ing caused by the increase of greenhouse gases is most evident over the land in the northern high latitudes. The enhanced surface temperature contrast between land and sea was a potential factor causing the enhancement of the Okhotsk High. The heating of northeastern Siberia most likely enhanced the summer Okhotsk High and caused the southward displacement of the westerly jet and the oceanic subarctic boundary and the resultant cooling in the northwestern Pacific region during the last deglaciation.

3.5. Millennial-Scale Variation of SST During 12–24 ka

[16] A warmer period between 13.3 and 14.6 ka was correlated with the North Atlantic Bølling-Allerød warm period (Figure 2b). Cooler periods of 12.3–13.3 ka and 14.6–16.9 ka were correlated with Younger Dryas and Oldest Dryas cold periods, respectively (Figure 2b). This correlation suggests a climatic linkage between the northwestern Pacific and the North Atlantic. The timing of the rapid warming in the northwestern Pacific (~12 ka) is almost the same as that in Greenland [*Stuiver et al.*, 1997]. The duration of warming was longer in the northwestern Pacific (~1500 years) than in Greenland (within 50 years [*Dansgaard et al.*, 1989]). A well-dated record from Lake Suigetsu, central Japan, revealed centennial-scale leads and lags of temperatures in Japan over Greenland in Bølling-Allerød and Younger Dryas periods [*Nakagawa et al.*, 2003]. Our millennial-scale SST record is not precisely correlated with the Lake Suigestu record, but consistent with the Greenland temperature records, although temperature changes were much faster in Greenland.

[17] The NAO influences the summer climate of the northwestern Pacific [*Ogi et al.*, 2004]. The warmer winter climate of Europe in a positive mode of the NAO corresponds to the cooler summer climate of the northwestern Pacific [*Ogi et al.*, 2004]. This modern relationship is opposite that observed during the last deglaciation in this study, suggesting that the direct NAO linkage was not a mechanism that resulted in the millennial climate change in the North Atlantic and the northwestern Pacific.

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References

Beaufort, L., T. de Garidel-Thoron, A. C. Mix, and N. G. Pisias (2001), ENSO-like forcing on oceanic primary production during the late Pleistocene, *Science*, *293*, 2440–2444.

Berger, A. (1978), Long-term variations of daily insolation and Quaternary climate changes, *J. Atmos. Sci.*, *35*, 2362–2367.

Chinzei, K., et al. (1987), Postglacial environmental change of the Pacific Ocean off the coasts of central Japan, *Mar. Micropaleontol.*, *11*, 273–291.

Clement, A. C., R. Seager, and M. A. Cane (1999), Orbital controls on the El Niño/Southern Oscillation and the tropical climate, *Paleoceanography*, *14*, 441–456.

Dansgaard, W., J. W. C. White, and S. J. Johnsen (1989), The abrupt termination of the Younger Dryas climate events, *Nature*, *339*, 532–534.

Goes, J. I., H. R. Gomes, A. Limsakul, W. M. Balch, and T. Saino (2001), El Niño related interannual variations in biological production in the North Pacific as evidenced by satellite and ship data, *Prog. Oceanogr.*, *49*, 211–225.

Herbert, T. D., et al. (2001), Collapse of the California Current during glacial maxima linked to climate change on land, *Science*, *293*, 71–76.

Igarashi, Y. (1996), A late glacial climate reversion in Hokkaido, northeast Asia, inferred from the *Larix* pollen record, *Quat. Sci. Rev.*, *15*, 989–995.

Indermühle, A., et al. (1999), Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica, *Nature*, *398*, 121–126.

Intergovernmental Panel on Climate Change (2000), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, edited by J. T. Houghton et al., 944 pp., Cambridge Univ. Press, New York.

Japan Oceanographic Data Center (1995), Temperature profile data set [CD-ROM JODC-1], Hydrogr. Dep. Mar. Safety Agency, Tokyo.

Kawamura, R., M. Sugi, T. Kayahara, and N. Sato (1998), Recent extraordinary cool and hot summers in East Asia simulated by an ensemble climate experiment, *J. Meteorol. Soc. Jpn.*, *76*, 597–617.

Kiefer, T., and M. Kienast (2005), Patterns of deglacial warming in the Pacific Ocean: A review with emphasis on the time interval of Heinrich event 1, *Quat. Sci. Rev.*, in press.

Lea, D. W., D. K. Pak, and H. J. Spero (2000), Climate impact of late Quaternary equatorial Pacific sea surface temperature variations, *Science*, *289*, 1719–1724.

Moore, T. C., et al. (1980), The reconstruction of sea surface temperatures in the Pacific Ocean of 18,000 B.P., *Mar. Micropaleontol.*, *5*, 215–247.

Nakagawa, T., et al. (2003), Asynchronous climate changes in the North Atlantic and Japan during the last termination, *Science*, *299*, 688–691.

Nitta, T. (1987), Convection activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation, *J. Meteorol. Soc. Jpn.*, *65*, 373–390.

Oba, T., and M. Murayama (2004), Sea surface temperature and salinity changes in the northwest Pacific since the last glacial maximum, *J. Quat. Sci.*, *19*, 1–12.

Ogi, M., Y. Tachibana, and K. Yamazaki (2004), The connectivity of the winter North Atlantic Oscillation (NAO) and the summer Okhotsk High, *J. Meteorol. Soc. Jpn.*, *82*, 905–913.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, *Nature*, *399*, 429–436, doi:10.1038/20859.

Prahl, F. G., L. A. Muehlhausen, and D. L. Zahnle (1988), Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions, *Geochim. Cosmochim. Acta*, *52*, 2303–2310.

Sawada, K., and N. Handa (1998), Variability of the path of Kuroshio ocean current over the past 25,000 years, *Nature*, *392*, 592–595.

Sawada, K., N. Handa, and T. Nakatsuka (1998), Production and transport of long-chain alkenones and alkyl alkenoates in a sea water column in the northwestern Pacific off central Japan, *Mar. Chem.*, *59*, 219–234.

Seki, O., K. Kawamura, M. Ikehara, T. Nakatsuka, and T. Oba (2004), Variation of alkenone sea surface temperature in the Sea of Okhotsk over the last 85 kyrs, *Org. Geochem.*, *35*, 347–354.

Smith, H. J., M. Fischer, M. Wahlen, D. Mastroianni, and B. Deck (1999), Dual modes of the carbon cycle since the Last Glacial Maximum, *Nature*, *400*, 248–250, doi:10.1038/22291.

Stuiver, M., T. F. Braziunas, P. M. Grootes, and G. A. Zielinski (1997), Is there evidence for solar forcing of climate in the GISP2 oxygen isotope record?, *Quat. Res.*, *48*, 259–266.

Thompson, P. R., and N. J. Shackleton (1980), North Pacific paleoceanography: Late Quaternary coiling variations of planktonic foraminifer *Neogloboquadrina pachyderma*, *Nature*, *287*, 829–833.

Yamamoto, M., M. Yamamuro, and R. Tada (2000), Late Quaternary records of organic carbon, calcium carbonate and biomarkers from site 1016 off Point Conception, California margin, *Proc. Ocean Drill. Program Sci. Results*, *167*, 183–194.

Yamamoto, M., T. Oba, J. Shimamune, and T. Ueshima (2004), Orbital-scale anti-phase variation of sea surface temperature in mid-latitude North Pacific margins during the last 145,000 years, *Geophys. Res. Lett.*, *31*, L16311, doi:10.1029/2004GL020138.

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