Orbital-scale anti-phase variation of sea surface temperature in mid-latitude North Pacific margins during the last 145,000 years

Masanobu Yamamoto, Tadamichi Oba, Junko Shimamune, and Toshinori Ueshima

Graduate School of Environmental Earth Science, Hokkaido University, Sapporo 060-0810, Japan

The late Quaternary records of alkenone sea surface temperature (SST) in the Japan and California margins showed orbital-scale anti-phase SST variations between the two margins. This east-west seesaw-like change agreed well with the long-term El Niño-Southern Oscillation (ENSO) behavior predicted by the Zebiak-Cane ENSO model [*Clement et al., 1999*] as regards both the timing and frequency during 0-60 ka and 120-145 ka, and is attributed to the precession-controlled change in tropical ENSO behavior. This anti-phase SST change was not clearly demonstrated during 60-120 ka. This finding suggests that the influence of tropical climatic dynamics on the mid-latitude North Pacific varied in response to glacial-interglacial cycles.

1. Introduction

Recently, the role of El Niño-Southern Oscillation (ENSO)-like variability in long-term climate changes has been discussed based on the results from a paleoclimatic model [*Cane, 1998; Clement et al., 1999*] and paleo-proxy data [e.g., *Heusser and Sirocko, 1997; Beaufort et al., 2001*]. Such studies have suggested that the tropical Pacific played a major role in forcing global climate changes to occur. However, our understanding of such long-term ENSO-like variability is still limited, especially in the extratropics.

In this study, we examined the influence of tropical orbital-scale ENSO-like variability on the mid-latitude North Pacific climate during the last glacial-interglacial cycle, in order to understand whether or not long-term ENSO-like variability has impacted climate on a global scale. Because the ENSO and decadal ENSO induce an east-west seesaw-like sea surface temperature (SST) variation in the mid-latitude North Pacific [e.g., *Zhang et al., 1997*], the difference between paleo-SSTs of the NE and NW Pacific margins can be an indication of the long-term ENSO-like variability. We have generated the alkenone SST records at the Japan (MD01-2421) and California (ODP 1014 and 1016) margins during the last 145,000 years (Fig. 1).

2. Materials and methods

A piston core MD01-2421 (45.82 m long) was collected from off of the coast of central Japan at 36°02'N, 141°47'E, and 2224 meters water depth [*Oba and KCRG, 2002*] (Fig. 1a). The age model was created by oxygen isotope stratigraphy [*Martinson et al., 1987*] of benthic foraminifera *Uvigerina* and *Bulimina aculeate*, by the calendar ages converted from the AMS C-14 ages of 11 samples of mixed planktonic foraminifera *Neogloboquadrina dutertrei* and *Globorotalia inflata* (0.29 to 42.274 ka) using the CALIB4.3 marine98 program [*Stuiver and Reimer, 1993*] and an equation of *Bard* [1998] with a 400-year global reservoir correction, and by the Aira-Tn ash layer at 28.59 ka [*Murayama et al., 1993*] (Fig, 2). This age model will be presented in more detail in Oba et al. [*manuscript in preparation, 2004*].

Cores 167-1014A-1H, 2H and 3H (0-16.9 mbsf) were collected in the Tanner Basin at 32°48'N, 118°54'W and 1165 meters water depth [*Lyle et al., 1997*] (Fig. 1b). The age model was created by oxygen isotope stratigraphy [*Martinson et al., 1987*] of benthic foraminifera *Uvigerina* [*Hendy and Kennett, 2000*], and by the calendar ages converted from the AMS C-14 ages of 7 bulk organic matter samples (2.30 to 20.55 ka) using the CALIB4.3 marine98 program and an equation of *Bard* [1998] with a 633-year reservoir correction for the California margin [*Ingram and Southon, 1996*] (Fig. 2).

Core 167-1016C-1H (0-9.2 mbsf) was collected from off of the coast of central California at 34°32'N, 122°17'W and 3834 meters water depth [*Lyle et al., 1997*] (Fig. 1b). The age model was created by the calendar ages converted from the AMS C-14 ages of 11 bulk organic matter samples (5.66 to 37.72 ka) using the same program and reservoir correction as Cores 167-1014A (Fig. 2).

The alkenone analysis and temperature calculation 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 at the Japan margin

The Japan margin of the mid-latitude NW Pacific has a subarctic boundary between the subtropical Kuroshio and subarctic Oyashio Currents. Core MD01-2421 was taken from a site located in the mixing zone of Kuroshio and Oyashio current waters, reflecting the latitudinal displacement of the subarctic boundary (Fig. 1a). The latitudinal displacement of the subarctic boundary during the late Quaternary has been suggested by previous studies [e.g., *Moore et al., 1980; Chinzei et al., 1987*]. The high sedimentation rate of Core MD01-2421 (average 33 cm/ky) enabled us to achieve a much higher resolution analysis than has been attained in previous studies.

At MD01-2421, the alkenone $U^{K'}_{37}$-derived SST changed from 13˚ to 23˚C during the last 145 kyrs (Fig. 3). The SST increases were delayed behind the MIS-1/2 and -5/6 boundaries by ~1 kyr and ~4 kyr, respectively (Fig. 3). Spectral analysis (Blackman-Tukey method) indicated a predominantly precessional 23-kyr period. The alkenone SST showed a positive correlation with the Kuroshio contribution indices [Kuroshio sp./(Kuroshio sp. + Oyashio sp.)], as based on nannofossil (r=0.57), planktonic foraminifera (r=0.77) and diatom assemblages (r=0.53) [*Oba et al., 2002; Oba et al., manuscript in preparation, 2004*]. This finding indicated that the alkenone SST variation mainly reflects the latitudinal displacement of the subarctic boundary.

A time series sediment-trap study demonstrated that the alkenone temperature reflects the summer SST at this site [*Sawada et al., 1998*]. The latitudinal position of the subarctic boundary associated with the westerly jet in summer is principally controlled by the intensity of the Okhotsk High. The strengthened Okhotsk High delayed the northward shift of the westerly jet 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. These modern observations imply that the alkenone temperatures at this site are related to the past variations of the summer Okhotsk High.

3.2. Paleo-SST at the California margin

The California margin is characterized by the California Current system, which is controlled by the intensity of the North Pacific High [*Hickey, 1979*] (Fig. 1b). The contribution of the subarctic water and the intensity of the California Current are enhanced during the summer due to the strengthened North Pacific High [*Hickey, 1979*]. The intensity of the Southern California Countercurrent is enhanced seasonally during late fall and winter [*Hickey, 1979*], as well as interannually in El Niño years due to the weakened North Pacific High [*Bograd and Lynn, 2001*]. ODP Site 1014 is located in the California Borderland, which is influenced by the northward invasion of the Southern California Countercurrent, whereas Site 1016 is located in the main path of the southward California Current (Fig. 1b).

At Site 1014, the SST changed from 12˚ to 19˚C during the last 158 ka, whereas at Site 1016, the SST changed from 9˚ to 15˚C during the last 38 ka (Fig. 3). The SST increase preceded the MIS-1/2 and -5/6 boundaries by ~8 kyr and ~6 kyr, respectively (Fig. 3). This early warming was more evident at Site 1014 than at Site 1016 (Fig. 3). This warming implies a stronger Southern California Countercurrent [*Herbert et al., 2001*], which is analogous to a modern El Niño condition [*Bograd and Lynn, 2001*], at the latest stage of the glacial periods. A strong cooling was observed around the MIS-2/3 and -3/4 boundaries (Fig. 3). *Coccolithus pelagicus*, a coccolithophoride specific to subarctic water in the North Pacific, was abundant in the same intervals [*Yamamoto and Tanaka, 1999*]. These observations imply an intensified California Current, which is analogous to a modern La Niña condition, during those periods.

The decline of the California Current during MIS-2 has been suggested by previous studies based on decreased paleo-productivity [*Lyle et al., 199*2] and increased meridional paleo-SST gradient [*Doose et al., 1997; Herbert et al., 2001*]. This decline was attributed to the depressed summer North Pacific High influenced by the semi-permanent development of a high-pressure cell over the expanded Laurentide ice sheet on the North American continent [*Kutzbach and Wright, 1985; Lyle et al., 1992*]. However, the change in the paleo-SST at Site 1014 was not in full agreement with the estimated volume change of the Laurentide ice sheet [*Boulton et al., 1985*]. In particular, a low SST and abundant *C. pelagicus* are indicative of a strong California Current in the late MIS-4, although MIS-4 was the period during which the ice sheet was at its second-largest phase of the last glacial period. This interpretation suggests that the volume of the Laurentide ice sheet was not the only factor affecting the California Current system.

3.3. East-west seesaw of paleo-SST variation

A comparison between the Japan and California margins demonstrated that the cool periods at the Japan margin correlate with the warm periods at the California margin (e.g., the late MIS-2 and the MIS-5/6 boundary) (Fig. 3). The reverse pattern was also found to be true (e.g., the MIS-2/3 and -3/4 boundaries) (Fig. 3). Apparently, the paleo-SSTs showed an anti-phase variation between the eastern and western margins of the North Pacific; this east-west seesaw effect is indicative of a strong link between those regions.

The east-west seesaw-like SST change in the mid-latitude North Pacific is characteristic of that induced by the modern interannual ENSO through atmospheric teleconnections [*NOAA, 2003*]. In El Niño years, the tropical convection center moves to the central and eastern equatorial Pacific. It weakens the North Pacific High in the summer, resulting in the warming of the California Borderland by the intensification of the Southern California Countercurrent [*Bograd and Lynn, 2001*]. At the Japan margin, 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, intensifying the summer North Pacific High and the California Current, cooling the California margin. It also 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*]. Since alkenones are produced mainly in the summer in both margins [*Prahl et al., 1993; Sawada et al., 1998*], the alkenone SST should reflect these anti-phase SST variations. Decadal-scale anti-phase change has also been observed in the instrumental records of the SST between the mid-latitude NE and NW Pacific [e.g., *Zhang et al., 1997*]. These modern observations suggest that tropical ENSO-like variability has exerted an influence on the mid-latitude North Pacific as an east-west SST seesaw occurring within a longer time frame.

We obtained the difference between SSTs of the NW and NE Pacific margins (ΔSST) during the last 145 kyrs by subtracting the SST of MD01-2421 from that of ODP 1014 (Fig. 3). The ΔSST varied between –7.1˚ and 2.5˚C with an average of –3.9˚C. A high ΔSST was observed in the late MIS-2 and the MIS5/6-bounary, while a low ΔSST was observed near the MIS-2/3 and the MIS-3/4 boundaries. Spectral analysis indicated 23-kyr (precession), 30-kyr (also found in equatorial Indo-Pacific paleoproductivity records [*Beaufort et al., 2001*]), 41-kyr (obliquity) and ~100-kyr (eccentricity) periods. The variation was large and pronounced at the precessional 23-kyr period during 0-60 ka (MIS-1 to MIS-3) and 120-145 ka (MIS-5e to MIS-6), whereas it was not clearly demonstrated during 60-120 ka (MIS-4 to MIS-5d).

A result of the calculation using a Zebiak-Cane ENSO model for the past 150 kyrs demonstrated that the frequency and amplitude of El Niño or La Niña varied in response to precessional forcing [*Clement et al., 1999*]. Our reconstructed record of ΔSST agreed well with the long-term ENSO behavior predicted by this Zebiak-Cane ENSO model [*Clement et al., 1999*], as regards both the timing and frequency during 0-60 ka and 120-145 ka (Fig. 3). This finding implies that the tropical ENSO-like variability has influenced the mid-latitudes through atmospheric teleconnections, even on an orbital timescale.

Although ΔSST changes can be predicted reliably using the long-term calculation of the Zebiak-Cane ENSO model during 0-60 ka and 120-145 ka, the ΔSST changes disagreed with the prediction during 60-120 ka (Fig. 3). *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 [*Clement et al., 1999*]. The disagreement between the mid-latitude North Pacific and the tropical Pacific suggests that the tropical influence on the mid-latitude North Pacific varied in response to glacial-interglacial cycles. The influence of tropical climatic dynamics extends to the Japan and California margins (32°N-36°N) in boreal summer, but it might have retreated during MIS-5d to MIS-5a. A possible explanation for this change would be that the activity of ENSO varied in response to glacial-interglacial cycles. *Tudhope et al.* [2001] reconstructed the annual variability in ENSO in eight different ages from fossil coral records and showed a damping of ENSO variance during the last glacial periods. This record is, however, not sufficiently continuous to allow us to understand the response of ENSO activity to glacial-interglacial cycles.

This study presents the new perspective that the orbital-scale anti-phase SST variation in mid-latitude North Pacific margins was a result of the long-term ENSO-like variability. Also, we hypothesize that the influence of tropical climatic dynamics on mid-latitude North Pacific varied in response to glacial-interglacial cycles. Extreme conditions (high ΔSST) appeared during the last two deglaciations, suggesting a linkage of the North Pacific SST seesaw to global climate change. Establishing more detailed features of the ENSO behavior and its related teleconnections in different climate phases or on different time scales is indispensable for understanding the role of the tropical ocean-atmosphere interactions in global climate change.

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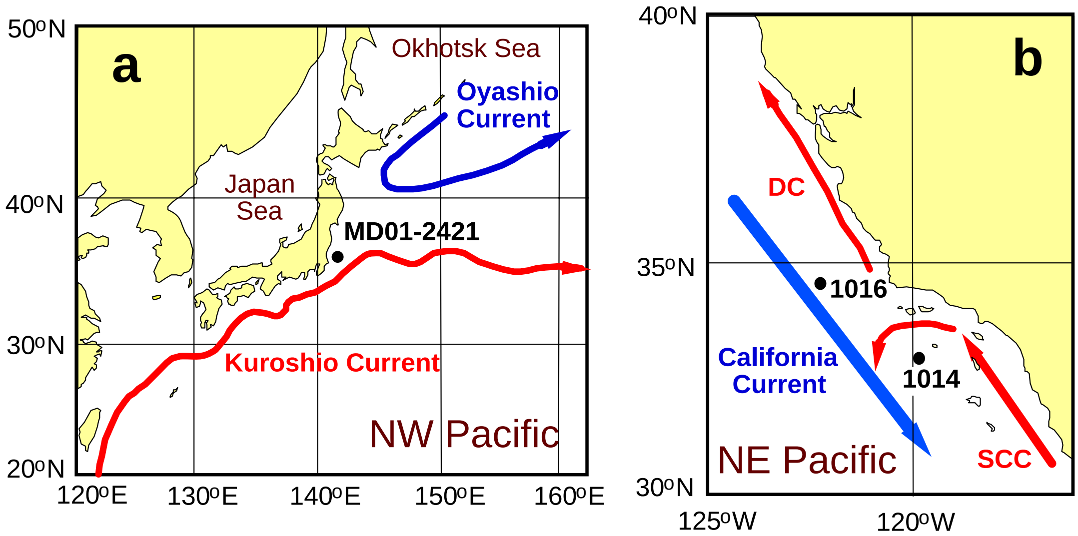
Figure captions

Fig. 1 Locations of Core MD01-2421 in NW Pacific (a) and ODP Sites 1014 and 1016 in NE Pacific (b). DC; the Davidson Current, SCC; the Southern California Countercurrent.

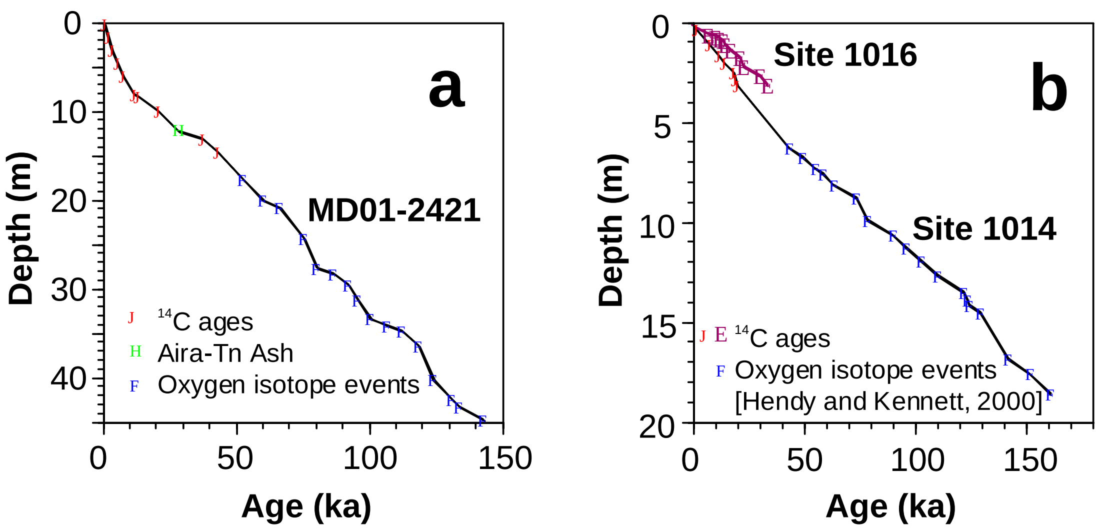
Fig. 2 Age depth models of Core MD01-2421 (a) [*Oba and KCRG, 2002; Oba et al., manuscript in preparation, 2004*] and ODP Sites 1014 and 1016 (b).

Fig. 3 Comparison between the NW and NE Pacific margins in the changes of alkenone $U^{K'}_{37}$-based sea surface temperature (SST), $\delta^{18}O$ of benthic foraminifera, SST difference between ODP 1014 and MD01-2421 (ΔSST) during the last 145 kys. Data regarding the SST for Site 1016, the benthic $\delta^{18}O$ for Site 1014, the benthic $\delta^{18}O$ for MD01-2421 refer to *Yamamoto et al.* [2000], *Hendy and Kennett* [2000] and *Oba et al.* [manuscript in preparation, 2004], respectively. The calculated NINO3 index [*Clement et al., 1999*] is shown for comparison.



a
b
Okhotsk Sea
Oyashio Current
Japan Sea
MD01-2421
Kuroshio Current
NW Pacific
50ºN
40ºN
30ºN
20ºN
120ºE
130ºE
140ºE
150ºE
160ºE
DC
1016
California Current
1014
SCC
NE Pacific
40ºN
35ºN
30ºN
125ºW
120ºW

Fig. 1



a
MD01-2421
Depth (m)
Age (ka)
14C ages
Aira-Tn Ash
Oxygen isotope events
b
Site 1016
Site 1014
14C ages
Oxygen isotope events
[Hendy and Kennett, 2000]

Fig. 2

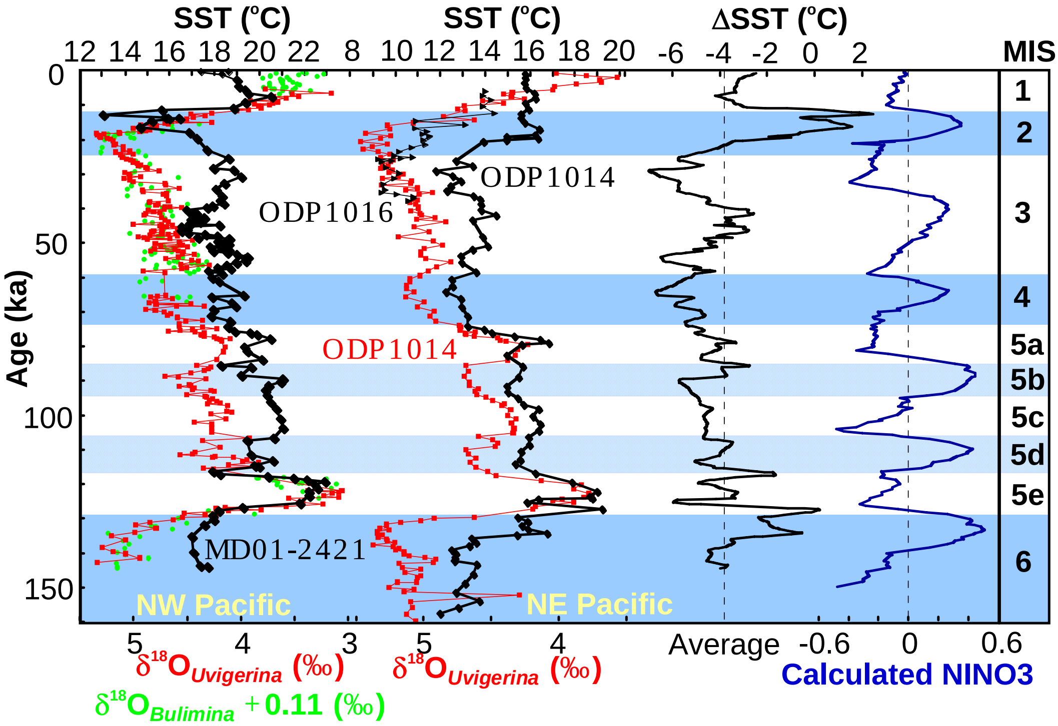

SST (°C)
12 14 16 18 20 22
SST (°C)
8 10 12 14 16 18 20
ΔSST (°C)
-6 -4 -2 0 2
MIS
0
50
100
150
Age (ka)
1
2
3
4
5a
5b
5c
5d
5e
6
ODP1016
ODP1014
ODP1014
MD01-2421
NW Pacific
NE Pacific
5 4 3
δ18O Uvigerina (‰)
δ18O Bulimina +0.11 (‰)
5 4
δ18O Uvigerina (‰)
Average
-0.6 0 0.6
Calculated NINO3

Fig.3