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Alkenone sea surface temperature in the Southern Ocean for the last two deglaciations

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Abstract. A piston core taken from the Tasman Plateau in the Southern Ocean has been studied for organic compounds to reconstruct the late Pleistocene marine environments. Here we report paleo sea surface temperature (SST) for the last two deglaciations using the unsaturation degree of alkenones (U^k_{37}') preserved in the marine sediments. The U^k_{37}' record indicates that the SST was at least 4°C lower than the present SST at the last glacial maximum (LGM), and the amplitude of paleo-SST is at most 5.2°C from the penultimate glacial (MIS-6) to the last interglacial warm period (the Eemian). Our results also demonstrate that the Eemian warm period in the Southern Ocean lasted only 3,000 years followed by a sharp cooling at around 120 kyr BP. The sharp cooling in the Southern Ocean seemed to occur a few millennia (2-3 kyrs) before the beginning of continental ice-sheet growth.

Introduction

The Southern Ocean occupies a significant position of world ocean and is characterized by several unique features: high-nutrient and low-chlorophyll (HNLC) conditions [e.g. *Coale et al.*, 1996], development of polar zonation surrounding Antarctica, deep convection to intermediate and deep waters. Reconstruction of the late Pleistocene sea surface temperature (SST) of the Southern Ocean is important for understanding paleoceanographic conditions such as the shift of the polar frontal zonation and its link to the Earth's climate system. In the early 1980s, the CLIMAP Project estimated SST for the last glacial maximum (LGM) and the last interglacial period (the Eemian) based on the planktonic microfossil assemblages in a large number of deep sea sediments [*CLIMAP Project Members*, 1981, 1984]. One of the significant findings was that the estimated SST in the low- to mid-latitudes at the LGM was not much different (<2°C) from the present SST. Further, the difference in the SST for the high-latitudes was not large (2-3°C) except in the North Atlantic and northwest Pacific. *CLIMAP Project Members* [1984] also concluded that SST of the last interglacial ocean was not significantly different from that of the modern ocean. However, the paleo-SST reconstructed at high-latitudes based on zooplanktonic microfossils contains uncertainty, because the diversity of foraminifera is much lower and their living depth ranges widely.

A geochemical thermometer, referred as U^k_{37} [*Brassell et al.*, 1986], is based on the analysis of long-chain alkenones (C_{37}) synthesized by certain haptophyte microalgae [*Marlow et al.*, 1990], and is characterized by a linear relationship to its growth temperature [*Prahl and Wakeham*, 1987]. This ratio is also unaltered through the food web in the water column and early diagenesis in the sediments [*Prahl et al.*, 1989, 1993]. The U^k_{37} ratios have so far successfully been used to reveal the past-SST variations in the equatorial Pacific [*Prahl et al.*, 1989; *Ohkouchi et al.*, 1994], North Pacific [*Prahl et al.*, 1995; *Herbert et al.*, 1995], equatorial Atlantic [*Brassell et al.*, 1986; *Jasper and Gagosian*, 1989; *Sikes and Keigwin*, 1994; *Schneider et al.*, 1995], and North Atlantic [*Eglinton et al.*, 1992; *Zhao et al.*, 1993, 1995; *Sikes and Keigwin*, 1996]. Here we report for the first time alkenone SST records for the last two deglaciation periods in the Southern Ocean.

Samples and methods

A piston core (KH94-4 TSP-2PC; 48°08.18'S, 146°52.45'E, 2321m water depth) and a multiple corer sample (TSP-2MC; 48°07.60'S, 146°53.99'E, 2283m water depth) were collected from the Tasman Plateau in the Southern Ocean during the R/V *Hakuho-Maru* cruise [*Ikehara et al.*, 1996; Fig. 1]. Sediments are mainly composed of calcareous foraminifera -nanno ooze ($CaCO_3$ content: 87-94%). It is verified that the multiple core TSP-2MC corresponds to the very surface sediments of piston core TSP-2PC based on comparison with magnetic susceptibility, color data, and oxygen isotopic values of these two core sediments.

A $\delta^{18}O$ stratigraphy was established for the subsurface dwelling planktonic foraminifera *Globigerina bulloides* (250 to 300 μm in test size; 40 specimens). These tests were reacted with 100% H_3PO_4 at 60°C and analyzed in a Finnigan MAT 251 mass spectrometer. The $\delta^{18}O$ results are expressed as per mil deviations from PDB (PeeDee Belemnite) standard. The core chronology was determined based on graphic correlation to the SPECMAP $\delta^{18}O$ record [*Imbrie et al.*, 1984] and AMS-^{14}C dating of planktonic foraminifera *G. bulloides* (see Fig. 3a). The AMS-^{14}C dates were obtained using the graphitization method [*Nakamura et al.*, 1987; *Kitagawa et al.*, 1993] and were corrected for a constant surface water age of 400 years [*Bard*, 1988]. The averaged sedimentation rate was estimated to be 1.5 cm/kyr.

The U^k_{37} values were obtained by the following procedure. The frozen sediment samples were cut at 2 cm intervals. Approximately 20 g of wet sediments were extracted for lipids with methanol/dichloromethane (3:1) and then

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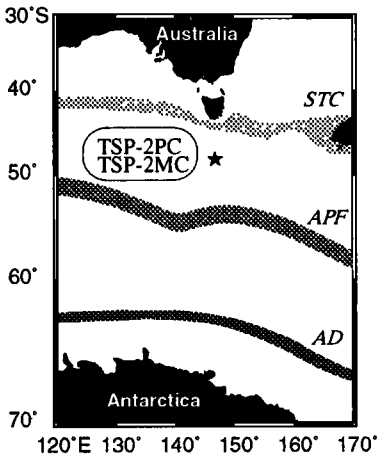

Figure 1. Location map of the deep sea cores TSP-2PC and TSP-2MC collected from the Tasman Plateau in the Southern Ocean and hydrographic conditions. STC : Subtropical Convergence zone, APF : Antarctic Polar Front zone, AD : Antarctic Divergence zone. Subantarctic Water properties between STC and APF are characterized by relatively warm and saline waters. In contrast, Antarctic Surface Water between APF and AD are characterized by cool and less saline waters.

dichloromethane/methanol (10:1) using an ultrasonic homogenizer. The extracts were isolated by a centrifuge and washed with 50 ml of 0.15M HCl to remove salts contained in the sediments, and then saponified with 0.5M KOH/methanol under a reflux. Neutral components were separated by extraction with dichloromethane/*n*-hexane (10:1). They were further divided into four sub fractions on a Pasteur pipette column packed with silica gel (BIO-SIL A, 200-400 mesh) which was deactivated with 1 % water. The fraction containing long-chain alkenones was analyzed by a Carlo Erba 5160 gas chromatograph (GC) equipped with a cold on-column injector, a HP-5 fused silica capillary column (30 m x 0.32 mm i.d.; 0.25 μm film thickness), and a flame ionization detector (FID). Hydrogen was used as a carrier gas, and the column oven temperature was programmed from 70°C to 120°C at 30°C/min. and then to 320°C (30 min.) at 6°C/min. The GC peaks were processed using a Shimadzu Chromatopac C-R7A integrator. Identification of alkenones was conducted by comparing gas chromatographic retention times with previous work [*Ohkouchi et al.*, 1994]. U^{k}_{37}' values were obtained with the following definition [*Prahl et al.*, 1988]:

$$U^{k}_{37}' = [C_{37:2}] / ([C_{37:2}] + [C_{37:3}])$$

where $[C_{x:y}]$ denotes the concentration of the alkenone with x carbon number and y double bonds. Triplicate analyses of composite sediments showed that the analytical errors in the procedures were ±0.001 for U^{k}_{37}' values (i.e. ±0.03°C). $C_{37:4}$ alkenone has been detected in some sediment samples, however, its concentrations were generally low.

Results and Discussion

Core top alkenone SST

Long-chain C_{37}-C_{39} alkenones detected in the surface sediments (TSP-2MC, 0-1 cm) had a U^{k}_{37}' value of 0.448. Comparison of the annual SST cycle from *Levitus* [1982] with that derived from three calibrations of the U^{k}_{37} method (Fig. 2) shows that the SST calculated using the calibration of *Prahl et al.* [1988] is similar to the summer SST near the sampling site. Therefore, we decided to use the following equation for the calculation of the past SST, whose precision is about 0.5 °C [*Prahl et al.*, 1988].

$$T\ (°C) = (U^{k}_{37}' - 0.039) / 0.034$$

A slight difference between the alkenone SST (12.0°C) and the summer Levitus SST (11.1°C; see Fig. 2) may be caused by a difference of the data source: the former represents an average SST for a few millennia whereas the latter represents at best few decades.

Glacial-interglacial variation of alkenone SST

Our U^{k}_{37}' values ranged from 0.281 to 0.465 during the last deglaciation (last 30 ka; MIS-3 to Holocene) and from 0.385 to 0.563 during the penultimate deglaciation (110-145 ka; MIS-6 to MIS-5d). Figure 3 demonstrates changes in the alkenone SST and planktonic $\delta^{18}O$ [*Ikehara*, 1997]. The alkenone SST between LGM and Holocene varied from 8.1 to 12.5°C (Fig. 3b), whereas those between MIS-6 and MIS-5e ranged from 10.2 to 15.4°C (Fig. 3c). The SST difference between LGM and Holocene is 4.4°C, and that for the penultimate deglaciation is 5.2°C. Thus, we conclude that the alkenone SST shifted by ca. 5°C during the last two glacial/interglacial climate variations in the Tasman Plateau region. These results suggest that SST variations in this region were greater by ca. 2°C than the CLIMAP results [*CLIMAP Project Members*, 1981]. This larger amplitude of glacial/interglacial SST change agrees with the SST changes reconstructed from diatom assemblages in the sediments from the Indian sector Southern Ocean, which showed 5-6°C difference for the glacial/interglacial periods [*Pichon et al.*, 1992]. The SST decrease in the glacial Southern Ocean may be

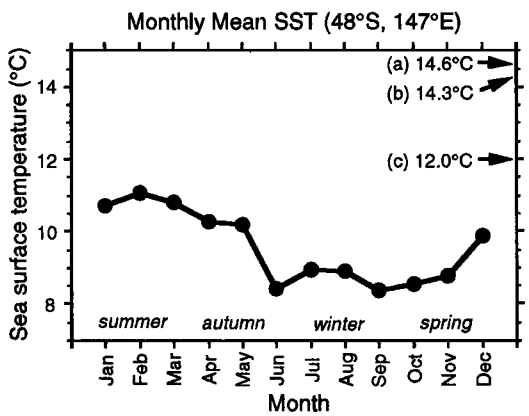

Figure 2. Annual surface temperature cycle of a location (48°S, 147°E) close to TSP-2PC and TSP-2MC [*Levitus*, 1982]. Alkenone SST for the surface sediments (TSP-2MC, 0-1cm) calculated by three calibrations are shown, as follows; (a) the linear field data calibration of *Sikes and Volkman* [1993] in the Southern Ocean (U^{k}_{37}' = 0.0414T - 0.156), (b) the calibration of *Brassell* [1993] based on global combined field data (U^{k}_{37}' = 0.037T - 0.083), and (c) the calibration of *Prahl et al.* [1988] based on cultures of *Emiliania huxleyi* (U^{k}_{37}' = 0.034T + 0.039).

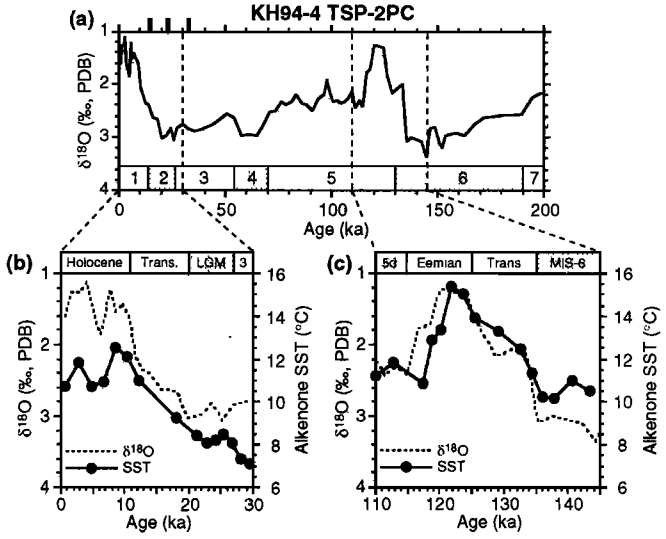

Figure 3. (a) Changes of the planktonic foraminiferal $\delta^{18}O$ in the sediment core (TSP-2PC) collected from the Tasman Plateau in the Southern Ocean. Odd numbers mean interglacial periods and shaded even numbers indicate glacial periods. AMS-^{14}C age levels are shown by bold marks on the top of the figure. (b) Changes in the planktonic foraminiferal $\delta^{18}O$ and sea surface temperature (SST) reconstructed from the U^{k}_{37}' index during the last deglaciation (MIS-3 to Holocene ; 0-30 ka). (c) Same as (b) but for penultimate deglaciation (MIS-6 to MIS-5d; 110-145 ka). For the definition of U^{k}_{37}', see the text. Estimated SST was calculated by using the following equation: T (°C) = (U^{k}_{37}' - 0.039) / 0.034 [*Prahl et al.*, 1988], where T denotes a haptophyte growth temperature.

caused by northward shift of the Antarctic Polar Front (APF) at that time.

Although the alkenone SST curve from LGM to Holocene is similar to that from MIS-6 to MIS-5e, the reconstructed SST values of the last deglaciation are systematically lower by ca. 3 °C compared to those for the penultimate deglaciation. In contrast, the foraminiferal results did not show a systematic shift of $\delta^{18}O$ values, which has been fluctuated mainly by ice volume. Thus, the systematic shift of alkenone SST between the last and penultimate deglaciations suggests that main contributor (coccolithophorid) to the C_{37} alkenones was different in the Southern Ocean for the last two deglaciations. In fact, the abundance of *E. huxleyi* decreased during the penultimate deglaciation in comparison with those of the last deglaciation [*M. Horikoshi and H. Okada*, pers. commun., 1997]. Alternatively, an excursion of the polar frontal zone and salinity change probably caused by evaporation to precipitation balance may contribute to the systematic shift of the alkenone SST between two deglaciations.

Eemian SST changes

The highest SST (15.4°C) in the Eemian was recorded at around 122 kyrs BP when the $\delta^{18}O$ values became minimum, and the alkenone SST dropped abruptly by 4.5°C (similar to glacial SST) in the middle of the Eemian (Fig. 3c). Based on the analyses of grain size and composition of sediments, no significant change was suggested in sedimentary processes at this period. Assuming a constant sedimentation rate during the Eemian, we estimated that the warmest period higher than 15°C lasted only ca. 3,000 years and ended at around 120 kyrs BP. The climate of the Eemian was thought to be stable and similar to that of the Holocene [e.g. *CLIMAP Project Members*, 1984]. However, our results suggest that the Eemian SST in the Southern Ocean is not stable throughout this period, and that rapid cooling occurred at around 120 kyrs BP. It is likely that this abrupt cooling took place entirely in the Southern Ocean, because similar cooling of mid-Eemian have been found in sediment cores recovered from other regions in the Southern Ocean [e.g. *Martinson et al.*, 1987; *Pichon et al.*, 1992].

However, the cooling event is unlikely explained by any significant decrease in the continental ice volume, because planktonic $\delta^{18}O$ values did not show a positive peak during the mid-Eemian (Fig. 3c). These results suggest that the cooling of the Southern Ocean preceded the significant increase of the continental ice sheets by 2-3 kyrs and that the global cooling from the last interglacial to glacial, which is recorded in the oxygen isotope signal of foraminifera, was triggered by an abrupt cooling of the high latitudes. We believe that this documented offsets in time between SST and $\delta^{18}O$ shifts are real records and cannot be explained by a bioturbation process, which could cause a selective redistribution of foraminiferal fossils and coccolithophorid grains [*Hutson*, 1980], because the abundance of both *G. bulloides* and alkenones were observed to stay almost constant throughout the sediment sequence from 110 to 130 kyr BP.

Conclusions

Southern Ocean sediment cores were studied for long-chain alkenones to reconstruct the SST for the last two deglaciation periods in relation to the global glacial/interglacial cycles. Our results demonstrate that:

(1) The alkenone SST difference between glacial and interglacial in the Southern Ocean was found to be approximately 5°C, indicating that the amplitude of Southern Ocean SST fluctuation was twice greater than that reported by the CLIMAP projects.

(2) The SST for the Eemian appear to be higher than that of the Holocene by ca. 3°C.

(3) The Eemian warmest period lasted only 3,000 years followed by a sharp cooling at around 120 kyrs BP. This cooling event occurred a few millennia before the beginning of a large continental ice-sheet growth.

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