# Vertical thermal structure history in the western subtropical North Pacific since the Last Glacial Maximum

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[1] Variations in sea surface temperature (SST) and vertical thermal structure in the western subtropical North Pacific, which has the largest air-sea heat flux of the world's oceans, provide insights into the mechanisms of climate change related to air-sea interactions. Here, we present planktonic $\delta^{18}$O and Mg/Ca records from the western subtropical gyre of the North Pacific spanning the last 30 kyrs. The results indicate that subtropical SSTs were approximately 3°C lower during the last glacial than in the Holocene interglacial, indicating that glacial cooling occurred uniformly in the low to mid-latitudes of the western North Pacific. A decrease in intermediate depth temperatures at the late glacial suggests that the formation and/or advection of the subtropical mode water was enhanced due to a strong East Asian winter monsoon. The results suggest that the change in the thermal structure of the subtropical gyre was related to changes in East Asian monsoon activity. **Citation:** Sagawa, T., Y. Yokoyama, M. Ikehara, and M. Kuwae (2011), Vertical thermal structure history in the western subtropical North Pacific since the Last Glacial Maximum, *Geophys. Res. Lett.*, *38*, L00F02, doi:10.1029/2010GL045827.

## 1. Introduction

[2] The western subtropical North Pacific has the largest air-sea heat flux in the world's ocean because of its geography [*Kubota et al.*, 2002]. The Kuroshio Current transports large amounts of heat from low to mid-latitudes along the North Pacific western margin, while the northwest wind associated with East Asian winter monsoon (EAWM) effectively removes heat from the ocean. As a result of winter cooling, the winter mixed layer reaches water depths of a few hundred meters. Subtropical mode water (STMW) is formed in the winter deep mixed layer to the west of the Izu Ridge along the southern part of the Kuroshio and the Kuroshio Extension [e.g., *Masuzawa*, 1969; *Suga and Hanawa*, 1990] (Figure 1a). The STMW is advected from its formation area into the western part of the subtropical gyre [e.g., *Suga and Hanawa*, 1995]. Because the water properties and distribution of STMW are considered to reflect wintertime heat loss, which is closely related with the intensity of EAWM [*Yasuda and Hanawa*, 1999], records of long-term variations in STMW are important in understanding the North Pacific climate system.

[3] Past seawater temperatures and the vertical gradient of seawater are keys for understanding changes in the upper ocean heat content and stratification. However, there are few paleotemperature data for the subtropical North Pacific because of a lack of appropriate sediment containing carbonate fossils. Here we present paleotemperature records for the western subtropical gyre (the downstream area of STMW) using multi-species Mg/Ca and $\delta^{18}$O analyses of planktonic foraminifera in order to understand temperature gradients between the surface and intermediate water depths and the long-term STMW formation history from the Last Glacial Maximum (LGM) (21 ± 2 ka [*Mix et al.*, 2001]) to the Holocene.

## 2. Materials and Methods

[4] A piston core ASM-5PC (28°23.00′N, 132°45.00′E) was extracted from 2678 m water depth of the Amami Sea Mount (ASM) in the western subtropical North Pacific during Cruise KH06-3 of R/V *Hakuho-maru* (Figure 1a). Core ASM-5PC is composed of calcareous ooze with two ash layers. The age model was constructed based on planktonic foraminiferal AMS radiocarbon dates at six layers combined with widespread tephra chronology (see auxiliary material for details).[1] The radiocarbon measurements were conducted under the protocol described in elsewhere [*Yokoyama et al.*, 2007, 2010]. Conventional $^{14}$C age was converted to calendar age using CALIB 5.0 [*Stuiver and Reimer*, 1993] with the marine04 dataset without $\Delta$R correction.

[5] Seven planktonic foraminiferal species (*Globigerinoides ruber*, *Globigerinoides sacculifer*, *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, *Globigerinella aequilateralis*, *Globorotalia inflata*, and *Globorotalia truncatulinoides*) were picked from three size fractions (250–355, 355–425, >425 $\mu$m) of a 1 cm slice of sediment. Pretreatment and analysis procedures followed the method described by *Sagawa and Ikehara* [2008]. Analytical errors were ±0.05‰ for $\delta^{18}$O and ±1% for Mg/Ca (1$\sigma$). Calculations of paleotemperatures were conducted according to the calibration of *Dekens et al.* [2002], which included the correction factor for the effect of dissolution on Mg/Ca, that is a function of the water depth, for *G. sacculifer* and *N. dutertrei*, and the calibration of *Anand et al.* [2003] for *G. inflata*.

## 3. Results and Discussion

### 3.1. Multi-species $\delta^{18}$O and Mg/Ca Results

[6] Downcore $\delta^{18}$O results for the seven species show similar variations over the deglaciation, however, there are some differences in the $\delta^{18}$O values and the timing of the

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045827.

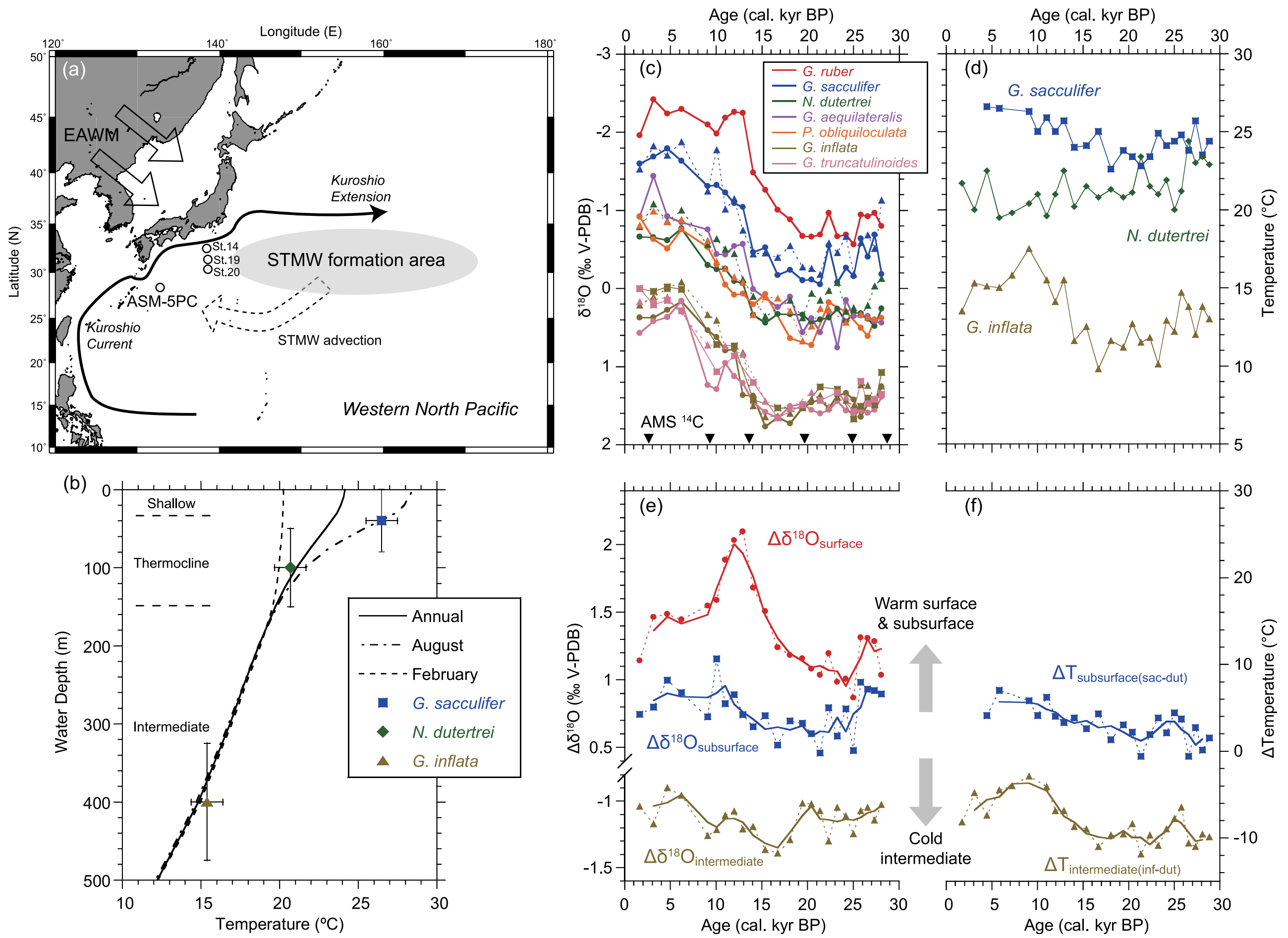


**Figure 1.** (a) Map showing the core site of ASM-5PC and reference sites. The schematic diagram of the STMW formation area and the direction of STMW advection are also shown. (b) The vertical temperature profile of annual mean and monthly mean of August and February of the upper 500 m of the water column at the core site (World Ocean Atlas 2005 [*Locarnini et al.*, 2006]). The Holocene mean Mg/Ca temperature of three species are plotted versus approximate habitat water depth of each species. (c) $\delta^{18}$O results from seven foraminiferal species from 250–355 $\mu$m (circles), 355–425 $\mu$m (triangles with dashed lines), and >425 $\mu$m (squares with thin lines) size fractions. AMS $^{14}$C age control points are shown by triangles on the bottom axis. (d) Mg/Ca temperatures of *G. sacculifer* (squares), *N. dutertrei* (diamonds), and *G. inflata* (triangles). (e) The $\delta^{18}$O difference ($\Delta\delta^{18}$O) between surface and thermocline ($\Delta\delta^{18}O_{surface}$, circles), subsurface and thermocline ($\Delta\delta^{18}O_{subsurface}$, squares), and intermediate and thermocline ($\Delta\delta^{18}O_{intermediate}$, triangles). (f) Mg/Ca-temperature difference between *G. sacculifer* and *N. dutertrei* (squares) and *G. inflata* and *N. dutertrei* (triangles).

inferred deglaciation between species (Figure 1c). These differences reflect the habitat of each of the foraminiferal species. We categorized the $\delta^{18}$O results into four groups based on their values, shallow-water species (surface and subsurface), thermocline- and intermediate-water depth species. The first group, which consists only of *G. ruber*, has the lightest $\delta^{18}$O values. The second group consists of *G. sacculifer*. The third group consists of *N. dutertrei*, *G. aequilateralis*, and *P. obliquiloculata*, and the last group consists of *G. inflata* and *G. truncatulinoides*. This categorization corresponds with the depth habitat of planktonic foraminifera summarized by *Bé* [1977]. The shallow-water species prefer warm stratified water, as seen in a sediment trap experiment conducted in the subtropical gyre of the western North Pacific [*Eguchi et al.*, 2003; *Mohiuddin et al.*, 2002]. The deeper and wider depth range habitat of *G. sacculifer* compared with *G. ruber* [e.g., *Fairbanks et al.*, 1982; *Tsuchihashi and Oda*, 2001] is reflected in the former's heavier $\delta^{18}$O values (Figure 1c). Therefore, we distinguished the two species and considered *G. ruber* and *G. sacculifer* to be summer surface and subsurface species, respectively. The Mg/Ca temperature of *G. sacculifer* was 26.5°C for the Holocene (Figure 1d), which agrees well with a summer subsurface (30–50 m) temperature of 27°C [*Locarnini et al.*, 2006] (Figure 1b). The third group, thermocline species, was seen in high abundance at the thermocline in depth-separated plankton tow experiments [*Tsuchihashi and Oda*, 2001]. It has been reported that their isotope and Mg/Ca temperatures reflect thermocline conditions [*Anand et al.*, 2003; *Mohtadi et al.*, 2009]. The Holocene temperature reconstruction for *N. dutertrei* shows 20.7°C and is consistent with the annual mean temperature at 100 m water depth, which corresponds to the thermocline. The fourth group, intermediate species, shows high abundance below the thermocline (~300–500 m water depth) during winter [*Tsuchihashi and Oda*, 2001], where vertical temperature gradients are small. The Holocene temperature estimation for *G. inflata* is 15.4°C, which agrees with the annual mean temperature from 300–400 m water depth (Figure 1b). This estimation agrees with the modern STMW temperature range of 14–19°C in the western North Pacific [*Masuzawa*, 1969; *Suga et al.*, 1997].

### 3.2. Temperature Changes in the Western Subtropical Gyre

[7] The $\delta^{18}$O of surface and sub-surface species began to decrease at 19 kyr BP (Figure 1c). Surface $\delta^{18}$O values reached Holocene values at 13 kyr BP after an interval of rapid decrease, whereas subsurface $\delta^{18}$O values showed a gradual decrease until 6 kyr BP. Although different timings of deglaciation were recorded in the two species, the magnitudes of the glacial-interglacial (G-IG) $\delta^{18}$O differences of both species are same. Mg/Ca temperatures from *G. sacculifer* show a 3.2°C cooling at the LGM (Figure 1d). This is comparable to the temperature drop of ~3°C from the same latitude of the Okinawa Trough [*Sun et al.*, 2005] and is almost similar or only slightly greater than the drop recorded in the western tropical Pacific of 2–3°C [*Lea et al.*, 2000; *Rosenthal et al.*, 2003; *Stott et al.*, 2002]. These results suggest that SSTs during the last glacial in the tropical and subtropical western North Pacific were almost uniformly 3°C lower than in modern times.

[8] Intermediate depth (~300–500 m) $\delta^{18}$O values are heaviest at 18–15 kyr BP, when other species' $\delta^{18}$O values have already started to decrease (Figure 1c). Mg/Ca temperatures of *G. inflata* also show low values in this period (Figure 1d). As a result, the deglacial warming of intermediate water lagged approximately 4 kyr behind that in surface waters. The G-IG temperature difference recorded in intermediate waters is 3.6°C, which is comparable to that recorded in subsurface waters. Conversely, temperatures obtained from *N. dutertrei* gradually decrease from the LGM to the Holocene by ~1°C. This suggests that the thermocline temperature was relatively stable through the termination I, and/or *N. dutertrei* has stayed within a preferred temperature range as suggested by *Wejnert et al.* [2010]. The larger variation of *G. inflata* temperatures than that of *N. dutertrei* implies that the mechanism that controlled the temperatures around 400 m was not caused by the winter vertical mixing at the core site because changes in winter mixing would influence the thermocline temperatures rather than the temperatures below the thermocline.

### 3.3. Vertical Thermal Structure History Since the LGM

[9] To discuss the changes in the vertical structure of the upper water column, $\delta^{18}$O difference between species ($\Delta\delta^{18}$O) has been widely used [e.g., *Mulitza et al.*, 1997; *Ravelo and Fairbanks*, 1992; *Spero et al.*, 2003]. This method extracts local hydrological changes from foraminiferal $\delta^{18}$O by canceling out the ice volume effect that is included in all foraminiferal $\delta^{18}$O variations. Because salinity is vertically stable in a subtropical gyre (34.45–34.83 psu for the upper 500 m), the main factor controlling $\Delta\delta^{18}$O should be temperature. Since each planktonic foraminiferal species prefers its own favorable surrounding environmental condition, we assume that each species is always dwelling within a certain water depth range as shown in Figure 1b. Figure 1e shows $\delta^{18}$O differences ($\Delta\delta^{18}$O) of surface, subsurface, and intermediate species from thermocline species (see auxiliary material for details). When $\Delta\delta^{18}O_{surface}$ or $\Delta\delta^{18}O_{subsurface}$ values are higher, the temperature difference is larger due to strong summer stratification and shallow thermocline depth. When $\Delta\delta^{18}O_{intermediate}$ value is lower, the temperature difference between the thermocline and intermediate waters is larger. Since temperature variation at the thermocline is smaller than the intermediate depth (Figure 1d), larger temperature difference between them is attributed to decrease of the intermediate temperature which implies the enhanced formation of STMW. We also calculated the Mg/Ca temperature difference ($\Delta$T), by subtracting *N. dutertrei* temperatures from those of *G. sacculifer* and *G. inflata* (Figure 1f). $\Delta\delta^{18}$O and $\Delta$T show similar variations particularly since the LGM. The results of this study show the temperature response of each water depth since the last 30 kyr BP. The $\Delta\delta^{18}O_{surface}$ shows a significant peak (~2‰) at 15–11 kyr BP. This is attributed to the development of surface stratification due to deglacial warming, as indicated by a rapid decrease in *G. ruber* $\delta^{18}$O values. The lack of such variation in $\Delta\delta^{18}O_{subsurface}$ suggests that the surface warming was limited to the upper a few tens of meters. The coeval increase in $\Delta\delta^{18}O_{subsurface}$ and $\Delta T_{subsurface(suc\text{-}dut)}$ through the deglaciation indicate that the thermocline depth became gradually shallower, and that modern upper water stratification was established at ~10 kyr BP.

[10] Lower values are shown by both $\Delta\delta^{18}O_{intermediate}$ and $\Delta T_{intermediate(inf\text{-}dut)}$ at the late glacial between 14 and 19 kyr BP (Figures 1e and 1f). Modern observational results show that the intermediate temperature of the western subtropical gyre is strongly affected by the formation and advection of STMW [e.g., *Bingham et al.*, 1992; *Oka*, 2009]. When the STMW formation and/or advection are strong, the intermediate temperature of the STMW downstream area decreases. The modern intermediate temperature in the area of STMW formation shows an inverse relationship with the monsoon index (MOI) [*Hanawa and Kamada*, 2001; *Taneda et al.*, 2000]. When the EAWM is strong, expressed as a large MOI, decreased SSTs yield deep convection, resulting in low STMW temperatures [*Hanawa and Kamada*, 2001]. This relationship suggests that the STMW temperature is strongly affected by the atmospheric pressure system. The lowest intermediate temperature seen in our results seems to be associated with Heinrich Event 1 (HE1) (Figures 2a–2c). Paleoclimate evidence shows that the EAWM was strong during the last glacial, especially in HE1 [*de Garidel-Thoron et al.*, 2001; *Porter and An*, 1995; *Steinke et al.*, 2010]. The small temperature difference in the upper South China Sea is observed at HE1, which is attributed to the deep convection due to a strong EAWM (Figure 2d) [*Steinke et al.*, 2010]. The highest $\delta^{18}$O values in Chinese caves indicate that the relative intensity of the winter monsoon compared with the summer monsoon was significantly high at HE1 [*Wang et al.*, 2001] (Figure 2e). The synchronous variation suggests that the intermediate temperature decrease was closely related to EAWM activity. It is also suggested that the STMW temperature reflects the heat influx to the formation area by the Kuroshio Current [*Hanawa and Kamada*, 2001; *Yasuda and Kitamura*, 2003], i.e., higher intermediate temperature corresponds to greater heat influx. Low SSTs are observed at HE1 in three alkenone records from the latitudinal transect of 30–33°N on the 139°E line [*Sawada and Handa*, 1998] (Figure 2f), suggesting that the heat transport of the Kuroshio Current was reduced at that time. Hence, it is speculated that

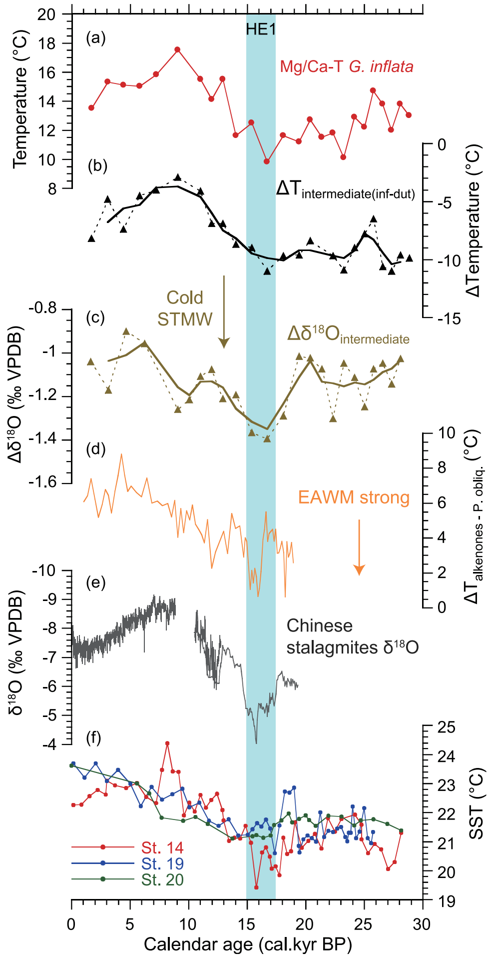


**Figure 2.** Comparison of the intermediate water proxy records in core ASM-5PC with other climate records. (a) Mg/Ca temperature of *G. inflata*. (b) $\Delta T_{intermediate(inf\text{-}dut)}$. (c) The $\delta^{18}O$ difference between intermediate and thermocline depth, $\Delta\delta^{18}O_{intermediate}$. (d) Thermal gradient between the surface and thermocline of the South China Sea, $\Delta T_{(alkenone\text{-}P.\ obliquiloculata)}$ [*Steinke et al.*, 2010]. (e) Stalagmite $\delta^{18}O$ records from Hulu and Dongge caves [*Wang et al.*, 2005, 2001; *Yuan et al.*, 2004]. (f) Alkenone temperature records of three sediment cores from the Nishishichitou Ridge [*Sawada and Handa*, 1998].

the strong EAWM combined with reduced heat transport by the Kuroshio Current resulted in enhanced STMW formation and reduced STMW temperatures at HE1.

[11] The LGM intermediate temperature (~12°C) was lower than the modern STMW temperature range of 14–19°C. The glacial subsurface temperature was also lower by as much as ~3°C. These imply that the glacial western subtropical heat content was much smaller than today. In addition, the latitudinal position of the Kuroshio front moved several degrees to south at HE1 [*Oba and Murayama*, 2004; *Sagawa et al.*, 2006], implying that the STMW formation area might shift to the south in association with the Kuroshio front. These data suggest that the glacial air-sea heat exchange in the western subtropical Pacific was different from today. To better understand the role of the subtropical ocean in climate change, records of spatial and temporal variations in temperature are much needed.

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