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Sea surface temperature variability in southern Okinawa Trough during last 2700 years

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[1] Most of the temperature reconstructions for the past two millennia are based on proxy data from various sites on land. Here we present a bidecadal resolution record of sea surface temperature (SST) in Southern Okinawa Trough for the past ca. 2700 years by analyzing tetraether lipids of planktonic archaea in the ODP Hole 1202B, a site under the strong influence of Kuroshio Current and East Asian monsoon. The reconstructed SST anomalies generally coincided with previously reported late Holocene climate events, including the Roman Warm Period, Sui-Tang dynasty Warm Period, Medieval Warm Period, Current Warm Period, Dark Age Cold Period and Little Ice Age. However, the Medieval Warm Period usually thought to be a historical analogue for the Current Warm Period has a mean SST of 0.6–0.8°C lower than that of the Roman Warm Period and Sui-Tang dynasty Warm Period. Despite an increase since 1850 AD, the mean SST in the 20th century is still within the range of natural variability during the past 2700 years. A close correlation of SST in Southern Okinawa Trough with air temperature in East China, intensity of East Asian monsoon and the El-Niño Southern Oscillation index has been attributed to the fluctuations in solar output and oceanic-atmospheric circulation. **Citation:** Wu, W., W. Tan, L. Zhou, H. Yang, and Y. Xu (2012), Sea surface temperature variability in southern Okinawa Trough during last 2700 years, *Geophys. Res. Lett.*, *39*, L14705, doi:10.1029/2012GL052749.

1. Introduction

[2] One of the key questions in the reconstruction of late Holocene climate is whether or not the 20th century warming is unusual over the past two millennia [*Moberg et al.*, 2005; *Mann*, 2007; *Christiansen and Ljungqvist*, 2011]. A clear answer to this question is crucial for the assessment of the relative contribution of human activities and natural processes to the observed warming [*Mann and Jones*, 2003]. As an important component of the Earth's climate system, East Asian monsoon (EAM) has received intensive attention because its variability greatly impacts livelihood of over two billion people. Studies based on stalagmites [*Wang et al.*, 2005], lacustrine sediments [*Yancheva et al.*, 2007], tree-rings [*Yang et al.*, 2000; *Wang and Zhang*, 2011] and historical documents [*Ge et al.*, 2004] have revealed a general weakening trend of EAM and a series of abrupt changes in the EAM intensity during the Holocene [*Xiao et al.*, 2006; *Wang et al.*, 2011]. These changes on different timescales correspond to a lowering Northern Hemisphere summer insolation and are likely linked to abrupt North Atlantic climate events [*Bond et al.*, 1997; *Wang et al.*, 2005; *Zhang et al.*, 2008]. Compared to terrestrial archives, marine sediment records of the EAM on decadal to centennial timescale are sparse [*Jian et al.*, 2000; *Wang et al.*, 2011]. Because the EAM is driven by air-pressure differences between the Pacific and Asian landmass, insufficient data on the ocean climate impedes our understanding of the operational mechanism of the EAM and the prediction of future climate change in this region.

[3] In this study we present a 25-year resolution record of sea surface temperature (SST) from the Southern Okinawa Trough (SOT) by analyzing tetraether lipids preserved in the sediments of Ocean Drilling Program (ODP) Hole 1202B (Figure 1). Okinawa Trough is one of the few locations where the seafloor under the Kuroshio Current (KC) lies above carbonate compensation depth. The KC, one of the two largest warm currents, plays a key role in the meridional transport of heat and water vapor to high latitudes. As a regional depocenter, the SOT receives enormous amounts of terrestrial materials from mainland China and the mountainous areas of Taiwan, and its high sedimentation rate allows high resolution paleoclimate studies [*Wei et al.*, 2005].

[4] Currently three proxies, namely UK'_{37}, Mg/Ca ratio and TEX_{86} (Tetraether index of tetraethers with 86 carbon atoms) are commonly applied for reconstructing SST. The first two are unfortunately not applicable for the ODP 1202B since alkenones are below the detection limit for most samples and the planktonic foraminifera are scarce throughout the core. In contrast, glycerol dialkyl glycerol tetraethers (GDGTs), the core member lipids of diverse archaea and bacteria [*Schouten et al.*, 2000; *Sinninghe Damsté et al.*, 2002; *Weijers et al.*, 2006], can be easily detected on high performance liquid chromatography-mass spectrometry (HPLC-MS). The TEX_{86} has been proposed as a SST proxy because the relative number of cyclopentane isoprenoid GDGTs in marine crenarchaeota (Thaumarchaeota) increases with increasing growth temperature [*Schouten et al.*, 2002]. The original TEX_{86} proxy has been refined intoTEX^{H}_{86} and TEX^{L}_{86} for oceans with annual SST >15°C and <15°C, respectively [*Kim et al.*, 2010].

2. Experiment

[5] The ODP Hole 1202B (24°48′N, 122°30′E, 1274 m water depth; Figure 1) was collected during the ODP Leg

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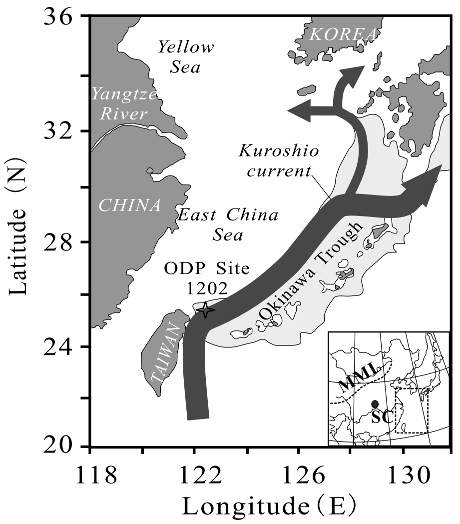

Figure 1. Location of ODP Site 1202 in Okinawa Trough. Black arrows indicate the main axis of Kuroshio Current and its branches. Black dots show the location of Sanbao Cave (SC) [*Dong et al.*, 2010] from the middle reach of Yangtze River. Dotted line represents modern monsoon limit (MML).

195 Expedition. In this study the uppermost 10 meter section was investigated. The sediments are exclusively of hemipelagic mud without any visible silt-sand layer. The clay-mineral assemblage mainly consists of illite, chlorite and kaolinite. The chronology was established on the basis of six accelerator mass spectrometer (AMS) ^{14}C dates (Table 1). Raw radiocarbon dates were converted into calendar years using the CALIB 6.1.1 program [*Stuiver et al.*, 1998]. The plot of calibrated ages versus core depth shows a correlation of r^2 = 0.981, indicating a linear sedimentation rate of 368 cm/kyr. Thus the top 10 meter section spans the past ca. 2700 years, and the samples (n = 109) for GDGTs analyses represent an average resolution of ca. 25 years.

[6] For GDGT analysis, freeze-dried sediments (ca. 5 g) were homogenized and ultrasonically extracted three times (15 min) with 20 ml of methanol, methanol:dichloromethane (1:1) and dichloromethane. The extracts were separated into aliphatic hydrocarbons (hexane), ketones (hexane:ethyl acetate; 9:1) and polar fractions (methanol) on a silica gel column. The polar fractions were spiked with a C_{46} GDGT (internal standard) and analyzed on an Agilent 1200 HPLC-MS [*Hopmans et al.*, 2004]. Separation was achieved in normal phase on an Alltech Prevail Cyano column (150 × 2.1 mm, 3 μm) with hexane:propanol 99:1 (v:v) as eluent (flow rate of 0.2 ml/min), isocratically for first 5 min, and a linear gradient to 1.8% propanol at 45 min. Each sample was run in duplicate and the average standard deviation is 0.003 for TEX_{86}, corresponding to ca. ±0.2°C. The SST reconstruction is based on *Kim et al.* [2010]: SST (°C) = 68.4*TEX^H_{86} + 38.6(r^2 = 0.87, p < 0.0001). Another GDGTs-based proxy, the BIT (Branched versus Isoprenoid Tetraethers) index, has been used for monitoring relative contributions of terrestrial organic carbon in marine sediments since soil/peat and open ocean sediments have the BIT values of 0.9–1 and close to 0, respectively [*Hopmans et al.*, 2004].

Table 1. AMS Results for Mixed Planktonic Foraminifera in ODP Hole 1202B

Depth (cm)	^{14}C Age	Std. Dev.	Calibrated YBP[a]	1δ Range (YBP)[a]	Calendar Age[a]
95	580	90	170	270-67	1780 AD
290	1150	90	680	867-523	1270 AD
515	1880	60	1390	1461-1314	560 AD
700	2090	120	1630	1787-1495	320 AD
910	2865	25	2590	2676-2533	640 BC
1088[b]	3153	40	2900	2962-2825	950 BC

[a] All ages were calibrated using the CALIB 6.1.1 program [*Stuiver et al.*, 1998]. A standard reservoir age correction (ΔR) of (35 ± 25) years for the Okinawa Trough [*Wei et al.*, 2005].

[b] The dating data is from *Wei et al.* [2005].

3. Results and Discussion

3.1. Late Holocene SST Variability in SOT

[7] Before reconstructing SST, we estimated the influence of terrestrial inputs on TEX_{86} because in the marine settings where terrestrial input is significant, isoprenoid GDGTs from soil/peat can bias TEX_{86}–SST proxy [*Weijers et al.*, 2006]. The sediments from the ODP Hole 1202B showed remarkably low BIT values (0.03 to 0.09; Figure 2), suggesting negligible contributions of soil organic carbon [*Hopmans et al.*, 2004]. The low BIT values in the SOT are likely caused by large contributions of fossil organic carbon [*Kao et al.*, 2008] or the high degradation of terrestrial-derived branched GDGTs during fluvial transport [*Zhu et al.*, 2011]. No matter which factor is more important, low BIT

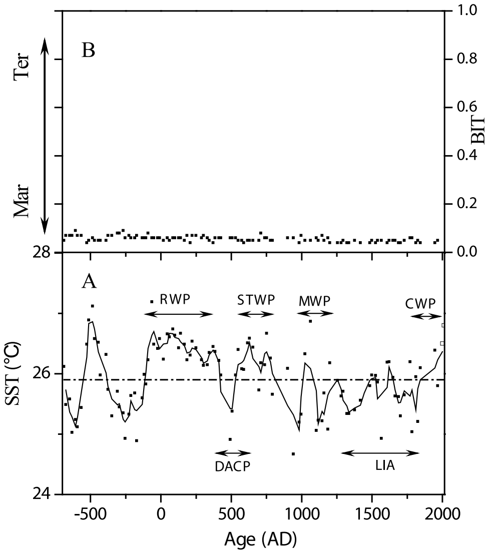

Figure 2. (a) Sea surface temperature (SST) for Southern Okinawa Trough using sediments from ODP Hole 1202B. Dashed line represents mean SST of the entire studied period while solid line is three-point running mean. (b) Branched versus isoprenoid tetraether index (BIT) indicative of relative contribution of terrestrial (Terr) and marine (Mar) organic carbon. The data point expressed in open square is from the satellite derived mean annual SST (http://www.nsof.noaa.gov). RWP: Roman Warm Period; DACP: Dark Age Cold Period; STWP: Sui-Tang dynasty Warm Period; MWP: Medieval Warm Period; LIA: Little Ice Age; CWP: Current Warm Period.

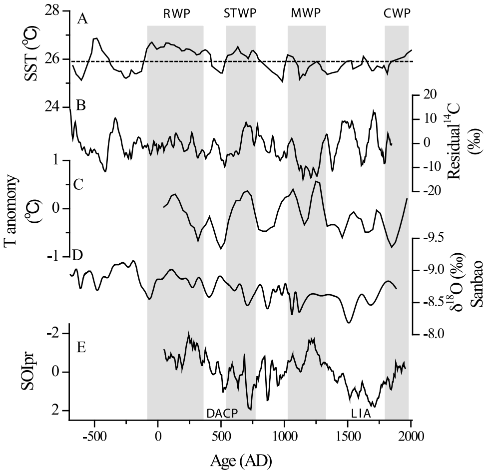

Figure 3. Comparison of (a) SST in SOT indicative of Kuroshio Current with (b) atmospheric residual Δ^{14}C [*Stuiver et al.*, 1998], indicating variable solar activity; (c) winter temperature anomaly in East China [*Ge et al.*, 2004], indicating intensity of East Asian Winter Monsoon (EAWM); (d) δ^{18}O values in Sanbao Cave [*Dong et al.*, 2010], indicating intensity of East Asian Summer monsoon (EASM); and (e) Southern Oscillation Index-like index (SOIpr) defined by *Yan et al.* [2011].

values suggest a minor influence of terrestrial input on the $\mathrm{TEX}_{86}^{\mathrm{H}}$-SST in the SOT.

[8] The reconstructed SST ranged from 24.9 to 27.5°C (Figure 2). An average SST of 25.9°C is close to the satellite derived annual mean SST for the SOT (e.g., 26.5°C for the year of 2000; http://www.nsof.noaa.gov). Recent studies for the mid-latitude western north Pacific [*Yamamoto et al.*, 2012] and the South China Sea [*Wei et al.*, 2011] also supported the TEX_{86}-based temperature close to the annual mean SST. Thus we interpret our $\mathrm{TEX}_{86}^{\mathrm{H}}$-SST as an annual instead of a seasonal signal. The amplitude of 2.6°C in SST variability reflects significant fluctuations of the KC in the late Holocene [*Jian et al.*, 2000]. Such a large SST amplitude has also been reported from the Mexico [*Richey et al.*, 2007], Sargasso Sea [*Keigwin*, 1996], Chesapeake Bay [*Cronin et al.*, 2003], Indo-Pacific Warm Pool [*Newton et al.*, 2006] and the western Antarctic Peninsula [*Shevenell et al.*, 2011], suggesting that 2–3°C amplitude natural climate variability is a widespread phenomenon in the late Holocene.

3.2. Implication for Late Holocene Climate Events

[9] Several centennial-scale warm/cool phases in the SOT coincide well with those documented for the late Holocene climate anomalies (Figure 2), including warm periods of ca. 120 BC–400 AD (Roman Warm Period; RWP), ca. 550–790 AD (Sui-Tang dynasty Warm Period; STWP), ca. 900–1300 AD (Medieval Warm Period; MWP) and ca. 1850 AD–present (Current Warm Period; CWP) [*Cronin et al.*, 2003; *Mann and Jones*, 2003; *Ge et al.*, 2004; *Patterson et al.*, 2010] and cool periods of ca. 400–550 AD (Dark Age Cold Period; DACP) and ca. 1300–1850 AD (Little Ice Age; LIA) [*Keigwin*, 1996; *Nyberg et al.*, 2002]. The coldest interval occurred around 600 BC. Whether this corresponds to the 2.7 ka climate event observed earlier [*Bond et al.*, 1997; *Wang et al.*, 2005] remains to be answered when we examine the lower part of the core 1202B.

[10] Based on our SST record, the MWP, usually thought to be a historical analogue for CWP, is characterized by large fluctuations from 25.1 to 26.8°C with a mean of 25.7°C, about 0.7°C lower than RWP (26.5°C) and STWP (26.3°C). On the centennial timescale, the mean SST of the 20th century (26.1°C) did not exceed the range of natural variability of the past 2700 years, such as RWP and STWP. The climate records from East China [*Ge et al.*, 2004], north Icelandic shelf [*Patterson et al.*, 2010] and Greenland [*Kobashi et al.*, 2011] also comprise centennial-scale warm periods during the first millennia AD, comparable to or even warmer than mean 20th century conditions. However, we acknowledge that if the SST in the SOT keeps increasing at the current rate (ca. 0.3°C per decade based on mean SST in 2000 and 2010; http://www.nsof.noaa.gov), the 21st century warmth will be indeed unprecedented in the context of the past 2700 years.

3.3. Correlation of SST in SOT With EAM and ENSO

[11] The variability of SST in the SOT coincides well with that of the solar activity indicated by residual atmospheric ^{14}C from tree-ring records where higher/lower ^{14}C concentrations correspond to lower/higher solar activity (Figure 3) [*Stuiver et al.*, 1998]. Spectral analysis resulted in the periodicities of ca. 400, 224, 159, 144 and 115 years for SST, some of which are close to the cycles of residual atmospheric ^{14}C concentrations (e.g., 204, 157, 129 years), supporting the hypothesis that solar activity is an important driver of SST in the SOT. However, solar irradiance variability during the late Holocene can cause global temperature to vary less than 1.0°C [*Gray et al.*, 2010], and thus is not sufficient to account for 2.6°C amplitude of SST oscillations. The remaining 1.6°C variability is attributed to internal forcings such as changes of KC and EAM intensity [*Jian et al.*, 2000].

[12] A significant statistical relationship (r = 0.30, $p < 0.01$, $n = 96$) was observed between SST variations in the SOT record and winter temperature changes in East China for the past two millennia at the resolution of 20 years [*Ge et al.*, 2004], such as the coeval occurrence of warm phases of RWP, STWP, MWP and CWP and cool phases of DACP and LIA (Figure 3). The SST variability also appears in phase with the δ^{18}O record of the Sanbao Cave from the middle reach of Yangtze River ($r = -0.28$, $p < 0.01$, $n = 93$), such as a long-term cooling (increasing δ^{18}O value) trend [*Dong et al.*, 2010]. Since the SST change in the SOT reflects the KC variability, while the winter temperature in East China and the stalagmite δ^{18}O of the Sanbao Cave are indicative of East Asian Winter Monsoon (EAWM) and East Asian Summer Monsoon (EASM), respectively [*Ge et al.*, 2004; *Dong et al.*, 2010], these correlations suggest a coupling evolution of the KC and EAM in the late Holocene. When the EAWM is strong (weak), strong (weak) cold and dry northern wind from the inner Asian continent blows over the KC region, causing more (less) intense convection of ocean water [*Xie et al.*, 2002]. As a result, large (small) amounts of heat are released to the atmosphere, causing a large (small) SST drop. On the other hand, during the summer, a strong (weak) KC would increase (decrease) SST in the KC region and transport more (less) amount of heat and

moisture to the high latitudes (including East Asian Continent), strengthening (weakening) EASM [*Jian et al.*, 2000; *Wang et al.*, 2011].

[13] Furthermore, the linkage between the KC variability and the tropical Pacific's climate is confirmed by a significant correlation between our SST record and the Southern Oscillation index (SOI_{pr}) for the period of 50 to 1950 AD at the resolution of 20 years ($r = -0.32$, $p < 0.01$, $n = 96$) [*Yan et al.*, 2011]. This correlation can be explained by a large scale meridional wind effect. During the El-Niño events, negative SST anomalies in the tropical western Pacific weaken the western Pacific Hadley Circulation [*Wang*, 2002]. As a result, the meridional northerly wind in the lower troposphere over the western Pacific becomes weaker, and more amounts of heat are transported from the tropical Pacific to the high latitude through intensified KC [*Qiu and Lukas*, 1996; *Wang*, 2002].

4. Conclusions

[14] We have presented a 25-year resolution record of SST in the SOT for the past 2700 years, from which four conclusions can be drawn. Firstly, previously reported late Holocene climate anomalies including RWP, DACP, STWP, MWP, LIA and CWP are unambiguously recorded in SST variability of the SOT. Secondly, the MWP (ca. 900–1300 AD), usually thought to be a historical analogue for the 20th warming, has mean SST lower than RWP and STWP and thus is not the best analogue for the 20th century warming at least in the SOT and East China. Thirdly, the 20th century warming in the SOT is still within the envelope of variability of the last 2700 years. Finally, a coupling evolution of KC, EAM and ENSO exists in the late Holocene, likely attributed to variability of solar activity and ocean-atmospheric circulation.

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