Geochemical Journal, Vol. 51, pp. e9 to e14, 2017 doi:10.2343/geochemj.2.0482

EXPRESS LETTER

Holocene sea surface temperature variations recorded in corals from Kikai Island, Japan

HIROTO KAJITA,[1] ATSUKO YAMAZAKI,[1,2] TAKAAKI WATANABE,[1] CHUNG-CHE WU,[3] CHUAN-CHOU SHEN[3] and TSUYOSHI WATANABE[1,2]*

[1]Faculty of Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan
[2]KIKAI Institute for Coral Reef Sciences, Kikai Town, Kagoshima 891-6151, Japan
[3]High-Precision Mass Spectrometry and Environment Change Laboratory, Department of Geosciences, National Taiwan University, Taipei 106, Taiwan, R.O.C.

(*Received December 31, 2016; Accepted April 26, 2017; Online published June 7, 2017*)

Understanding seasonal to interannual characteristics of the climate during the transition from the "Holocene Optimum" (7.0–5.0 kyr BP) to mid-Holocene cold and dry period (4.6–4.0 kyr BP) is important since it is related to the evolution and collapse of human civilization in East Asia. To investigate those characteristics, we reconstructed a seasonal scale sea surface temperature (SST) and measured oxygen isotope ratios ($\delta^{18}O$) in seawater ($\delta^{18}O_{seawater}$) using modern and fossil (4.9 kyr) corals from Kikai Island. Larger seasonal amplitudes observed among the reconstructed SST values and $\delta^{18}O_{seawater}$ change at 4.9 kyr suggest that the East Asian Monsoon (EAM) circulation might be stronger than the present-day. Our compiled coral records, along with the previous studies from Kikai Island, also suggest that the largest SST amplitude during the Holocene Optimum was recorded at 4.9 kyr and an abrupt cold climate shift occurred during the Holocene Optimum and the *Pulleniatina* Minimum Event (PME) in the north-western Pacific.

Keywords: Mid-Holocene, coral record, paleo-SST, paleo-SSS, Kikai Island

INTRODUCTION

The mid-Holocene is generally considered to have been warmer than the present day and is called the "Holocene Optimum". Recently, in growing number of studies it has been reported that the millennium scale climate perturbations existed during the mid-Holocene. The transition from the "Holocene Optimum" (7.0–5.0 kyr BP) to the mid-Holocene cold and dry period (4.6–4.0 kyr BP) was drastic and strongly related to the collapse of human civilizations (Wu and Liu, 2004). During this cooling event, several geological evidence from stalagmites in China indicate the weakening of the EAM, which caused a change in the distribution pattern of monsoon-related rain belts (Wang *et al*., 2005; Hu *et al*., 2008). Furthermore, the PME, which is known as a major cold event related to the weakening of the Kuroshio Current (KC), is recognized in the East China Sea (ECS) at 3.0–4.6 kyr BP (Ujiie *et al*., 2003; Xiang *et al*., 2007). However, the accurate timing and magnitudes of these events are not confirmed yet.

It is important to understand how monsoonal climate conditions were linked to human life in civilized societies, such as agriculture and fisheries. Therefore, in this study, we reconstructed monthly resolved SST and $\delta^{18}O_{seawater}$ variability at 4.9 kyr, recorded in a fossil coral from Kikai Island, Kagoshima, Japan.

Coral skeletons are widely used as high-resolution paleoenvironmental recorders of different time windows (e.g., Tudhope *et al*., 2001; Watanabe *et al*., 2011). For example, Sr/Ca ratios in coral skeletons are reliable proxies for SST (Beck *et al*., 1992). Correspondingly, oxygen isotope ratios ($\delta^{18}O$) in coral aragonite skeletons are controlled by SST and $\delta^{18}O_{seawater}$ (Weber and Woodhead, 1972). The subtraction of SST component from the $\delta^{18}O$ variation of the coral record represents a proxy of local $\delta^{18}O_{seawater}$ variability. Since $\delta^{18}O_{seawater}$ is controlled by the evaporation and precipitation ratio of the sea surface, it is directly proportional to Sea Surface Salinity (SSS) (Watanabe *et al*., 2001; Morimoto *et al*., 2007).

REGIONAL SETTINGS AND CORAL SAMPLING

Kikai Island is located in the easternmost part of the

*Corresponding author (e-mail: nabe@sci.hokudai.ac.jp)

Copyright © 2017 by The Geochemical Society of Japan.

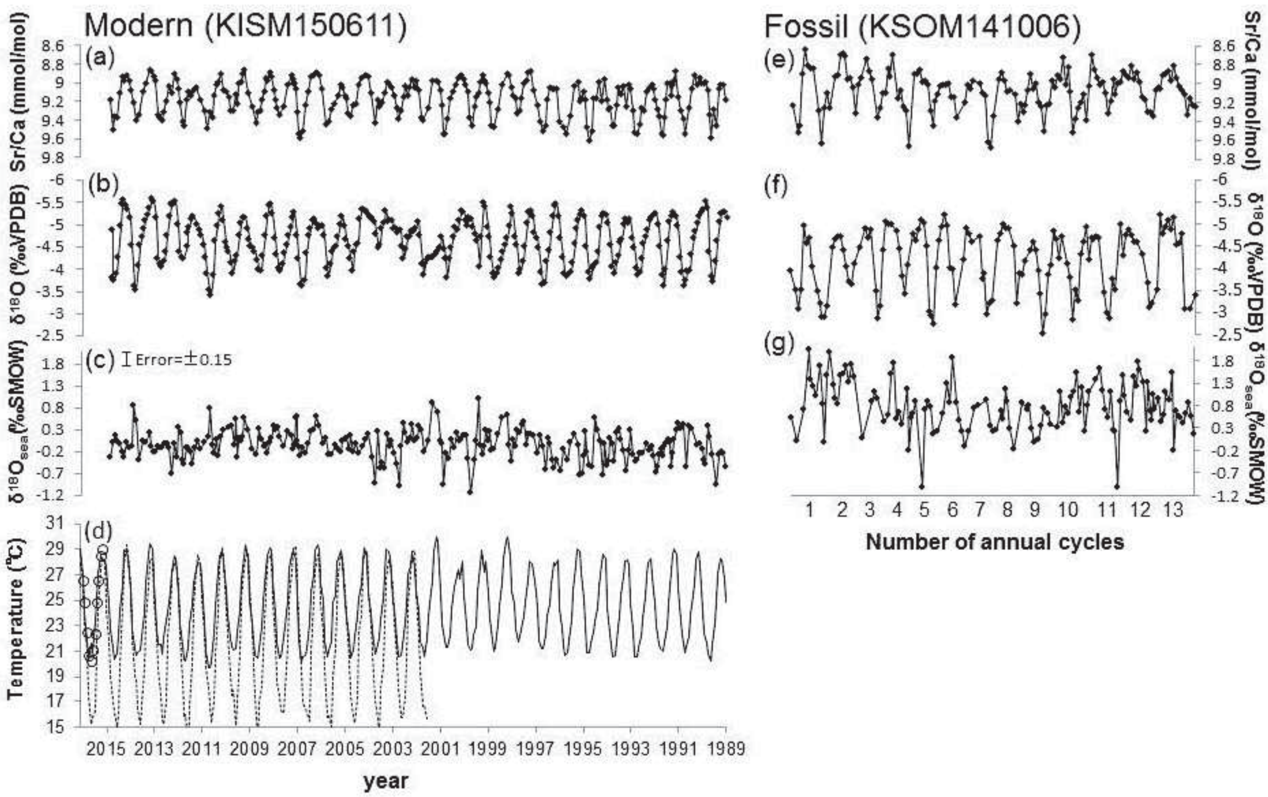

Fig. 1. (a) Sr/Ca ratios, (b) $\delta^{18}O$, and (c) reconstructed $\delta^{18}O_{seawater}$ from modern coral (KISM150611). KISM150611 has a record from 1989 to 2015. (d) Monthly SST fluctuations from the IGOSS data set at 28.5°N, 129.5°E (available online at: http://iridl.ideo.columbia.edu/) are shown with the solid line. The open circles represent SST in situ measurements (Shunmichi). Both SSTs show similar seasonal variations. The dotted line represents the air temperatures at Kikai Island, observed by the Japan Meteorological Agency. (e) Sr/Ca ratios, (f) $\delta^{18}O$, and (g) reconstructed $\delta^{18}O_{seawater}$ from the fossil coral (KSOM141006). KSOM141006 has annual records of 13 years.

ECS (Supplementary Fig. S1). At present, its sea surface hydrography is strongly influenced by the EAM and the KC. While the KC, flowing northeast of Kikai Island, originates from the Western Pacific Warm Pool and carries warm saline water to the ECS (Ujiie *et al*., 2003), the EAM drives seasonal hydrographic variability. More precisely, monsoonal winds and precipitation, alternating between cold, dry winter monsoon winds and warm, moist summer monsoon winds, bring seasonal SST and SSS variability to this region.

To investigate better the climate variability of the study area, we performed several methodologies on modern and fossil coral samples. Two samples of massive *Porites* sp. were collected from Shunmichi at the northeastern part of Kikai Island. One of the two samples is a modern coral, *KISM150611*, that thrives at a water depth of 2 m and taken in June 2015; the other is a fossil coral, *KSOM141006*, taken in October 2014 from an uplifted Holocene terrace at 3 m above the present mean sea level. The two samples were cut into 5-mm-thick slabs and X-rayed. X-ray diffraction (XRD) analysis and observation by scanning electronic microscopy (SEM) showed the fossil coral to be pristine (Supplementary Fig. S2). High precision U-Th dating for the fossil coral was carried out at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University. U-Th chemistry was performed on a class-100 bench in a class-10,000 clean-room. U-Th isotopic composition and contents were determined on a Thermo Fisher NEPTUNE multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) (Shen *et al*., 2012).

After ultrasonic cleaning, powdered samples were taken at a 0.9 mm interval along the maximum growth lines, yielding 12.5 and 11.8 subsamples/yr for the modern coral and the fossil coral, respectively. The $\delta^{18}O$ was analyzed in 20–35 μg subsamples using a stable isotope ratio mass spectrometer, Finnigan MAT253, equipped

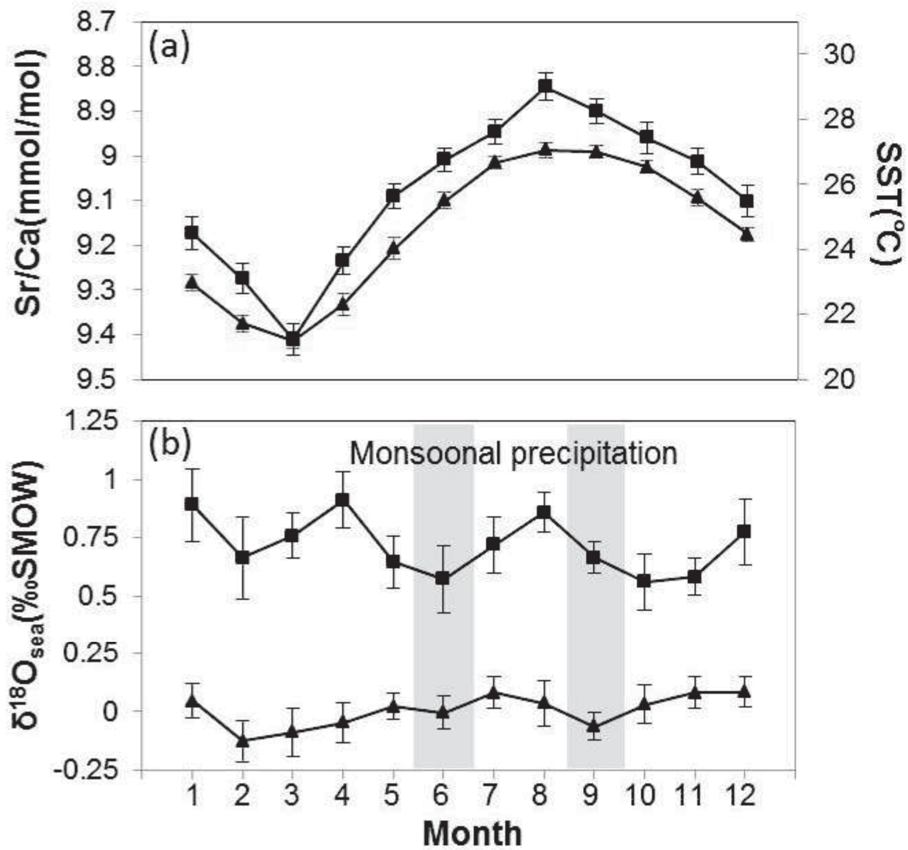

Fig. 2. Comparison of the averaged seasonal cycles of (a) Sr/Ca-based SSTs in the modern coral (triangles) and the fossil coral (squares), and (b) $\delta^{18}O_{seawater}$ from modern coral (triangles) and fossil coral (squares). Error bars (±1σ) indicate standard error for the whole interval. The gray bars represent the approximate present-day monsoonal rainy season (June and September) in Kikai Island.

Table 1. Summery of Sr/Ca-derived SSTs and $\delta^{18}O_{coral}$

	Reconstructed length (years)	Sr/Ca-based SST (°C)	$\delta^{18}O_{coral}$ (‰VPDB)
Modern	26		
Summer		28.9	–5.35
Winter		20.8	–3.78
Annual average		25.4	–4.68
Fossil (4.9 kyr)	13		
Summer		30.9	–4.96
Winter		20.7	–3.04
Annual average		26.7	–4.16

with an automated carbonate reaction device (KielIV). The internal precision for $\delta^{18}O$ was ±0.03‰ using replicate measurements of the NBS-19 standard (n = 30). Sr/Ca ratios were analyzed in 140–160 μg subsamples using inductively coupled plasma-atomic emission spectrometry (ICP-AES). The reproducibility was determined as ±0.05 mmol/mol for the Sr/Ca ratio using replicate measurements of the JCp-1 standard (n = 30).

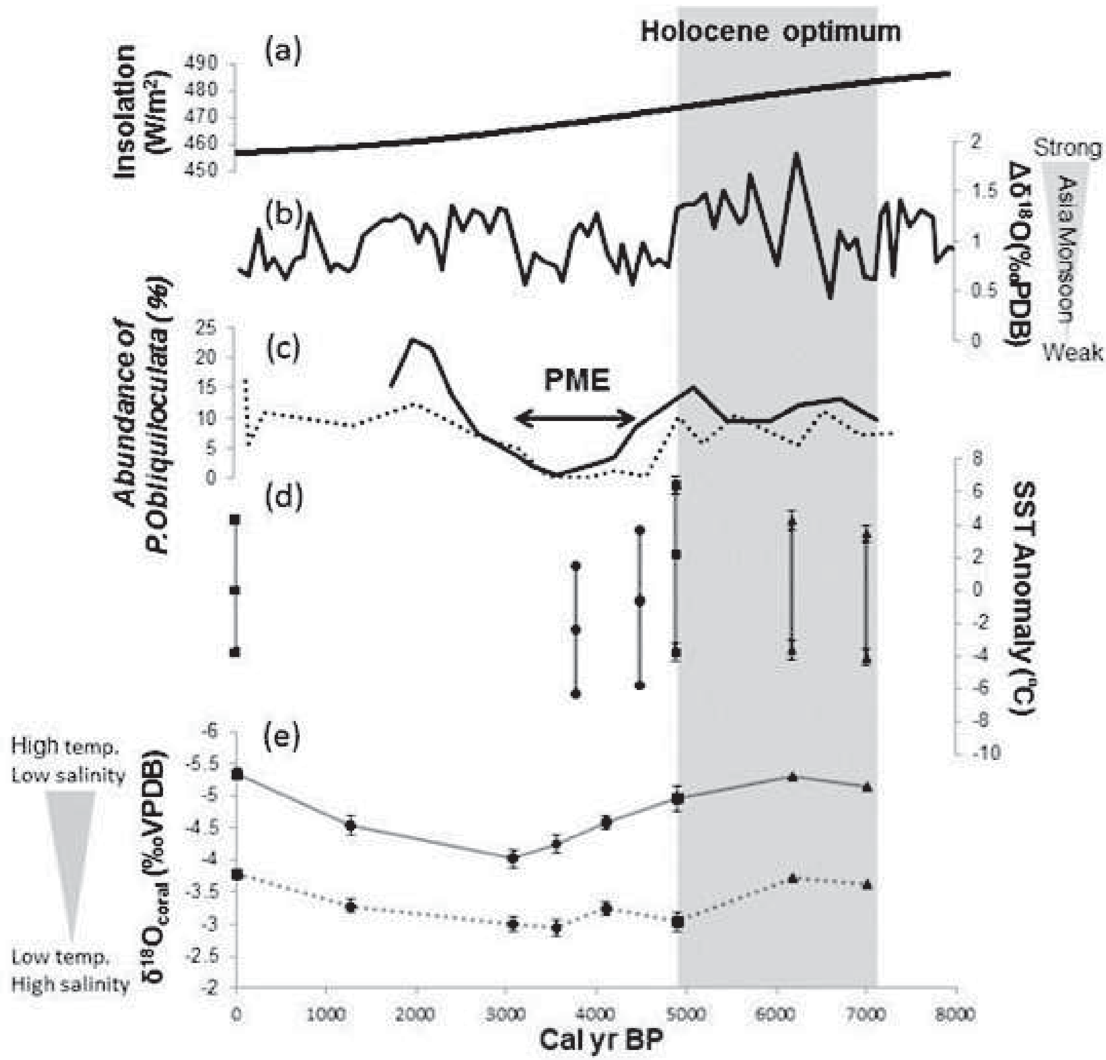

Fig. 3. Climate changes during the mid- to late-Holocene near the Okinawa Trough. The gray bar represents the period of Holocene Optimum. (a) Average summer insolation at 25°N (Lasker et al., 2004). (b) The difference between the two stalagmite $\delta^{18}O$ records ($\Delta\delta^{18}O$) from spatially separated Chinese caves (Hu et al., 2008). (c) The timing of the PME observed in core A7 from Xiang et al. (2007) (solid line) and core RN92-PC3 from Ujiie et al. (2003) (dotted line). (d) The reconstructed coral based on SST anomaly from this study (squares), Morimoto et al. (2007) at Kikai Island (triangles), Seki et al. (2012) at Kume Island (circles). The vertical bars represent seasonal SST amplitudes. (e) Coral $\delta^{18}O$ records obtained in this study (squares) and other records from Kikai Island; Abram et al. (2001) (open squares) and Morimoto et al. (2007) (open triangles). The solid and dotted lines represent summer and winter values, respectively.

RESULTS

The results of ^{230}Th dating are given in Supplementary Table S1. According to our results, the age of the fossil coral is 4959 ± 12 yrs relative to the chemistry date of March 2015 (≒4.9 kyr BP). A time series was prepared after ^{230}Th dating and plotted against the results of isotope and Sr/Ca measurements. The time series of $\delta^{18}O$ and Sr/Ca in modern and fossil corals show clear seasonal cycles corresponding to seasonal SST cycles (Fig. 2). The age model of modern coral geochemical records was determined by correlating seasonal minimal Sr/Ca to the seasonal maximal SST and vice versa (Figs. 1a and 1d). To calibrate the coral Sr/Ca-monthly SST relationship, a least squares regression analysis was performed using age control points during the period of 1990–2015. The given equation is:

$$\text{Sr/Ca (mmol/mol)} = 10.80\ (\pm 0.07) - 0.0643\ (\pm 0.0026) \times \text{SST}\ (^\circ\text{C})\ (r^2 = 0.93). \quad (1)$$

The errors are given as ±1σ. This equation is similar to Morimoto *et al.* (2007): Sr/Ca (mmol/mol) = 10.77 (±0.09) – 0.0665 (±0.0036) × SST (°C) (r^2 = 0.97).

Coupled records of coral $\delta^{18}O$ and Sr/Ca ratios have been used to reconstruct $\delta^{18}O_{seawater}$. Coral $\delta^{18}O$ is influenced by both local $\delta^{18}O_{seawater}$ and ambient temperature. The equation can be expressed as Eq. (2) (Juillet-Leclerc and Schmidt, 2001). The SST derived from the coral Sr/Ca was incorporated into Eq. (2).

$$\delta^{18}O_{coral}\ (‰VPDB) - \delta^{18}O_{seawater}\ (‰VSMOW) = 0.45–0.20\ (\pm 0.02)\ SST\ (°C). \quad (2)$$

The error of $\delta^{18}O_{seawater}$ [$\sigma(\delta^{18}O_{seawater})$] was calculated using the following formula (Cahyarini *et al.*, 2008):

$$\sigma(\delta^{18}O_{seawater})^2 = \sigma(\delta^{18}O_{coral})^2 + (\gamma/\beta\sigma_{(Sr/Ca)})^2, \quad (3)$$

where γ is the regression slope of coral $\delta^{18}O$ vs. SST; and β is the regression slope of coral Sr/Ca vs. SST. From this equation, the error was calculated as ±0.15‰ (±1σ).

The average monthly coral-derived SST and $\delta^{18}O_{seawater}$ were calculated to obtain the differences between the present day and 4.9 kyr BP (Fig. 2). For the modern coral, the maximum and minimum SSTs were related to the minimum and maximum Sr/Ca ratios, respectively. For the fossil coral, the maximum and minimum Sr/Ca ratios in each seasonal cycle were considered to be established in the lowest SST season (March) and the highest SST season (August), respectively. The records between summer and winter were interpolated to monthly resolution records based on the assumption that the coral calcification speed was identical during one-half a year.

Discussion

The SST derived from the fossil coral of age 4.9 kyr BP was higher than the modern coral by 1.3°C in the annual average and 2.0°C in the summer average (Table 1; Fig. 2a). In the coral reefs near the coast, summer SST is likely to be influenced by the air temperature (e.g., Sowa *et al.*, 2014). By contrast, in winter, the KC induces the SST to be warmer than the corresponding air temperature (Fig. 1d). A high summer SST indicates the warm conditions at 4.9 kyr BP close to the end of the Holocene Optimum. The warm conditions and high summer insolation at 4.9 kyr BP (Lasker *et al.*, 2004) might enhance a thermal contrast between the land and the oceans, which could cause a strengthening of the EAM, and therefore a higher amount of monsoonal precipitation. The paleo-$\delta^{18}O_{seawater}$ seasonal change, reconstructed from modern and fossil corals, shows a decrease during the monsoonal rainy season, between June and September (Fig. 2b). Accordingly, the greater decrease in $\delta^{18}O_{seawater}$ in fossil coral may suggest more intense monsoonal precipitation at 4.9 kyr BP than the present-day.

The mid- to late-Holocene environment near the Okinawa Trough was reconstructed using fossil corals from Kikai Island (Abram *et al.*, 2001; Morimoto *et al.*, 2007) and Kume Island (Seki *et al.*, 2012). Present-day temperatures of Kikai and Kume islands are nearly the same (0.1°C in summer and 0.7°C in winter from the last 30 year's Intergrated Grobal Ocean Services System (IGOSS) data set). Our compiled coral profile shows that the highest SST during the Holocene Optimum was recorded at 4.9 kyr BP and that SST dropped dramatically between 4.9 kyr BP and 3.8 kyr BP, coinciding with the Holocene Optimum (warmer phase) and the PME (colder phase), respectively. During this colder phase, several stalagmite records in China indicate the weakening of the EAM (Fig. 3b). The combined coral $\delta^{18}O$ record for Kikai Island reveals that the amplitude of seasonal differences during warmer phases (the present-day and the Holocene Optimum) was greater than those during the colder phase (the PME).

The cause of the PME is still controversial. The PME, characterized by a relatively low abundance of the foraminifera tests of *Pulleniatina obliquiloculata*, was explained to be the result of a reduction in transport by the KC (e.g., Ujiie *et al.*, 2003); however, this event was not recorded as a cold event in deep sea sedimentary cores from the KC basin (Sun *et al.*, 2005; Xiang *et al.*, 2007). Our results imply that a drastic lowering of SST and a weakening of the EAM occurred after the end of the Holocene Optimum could be some of the possible triggers of the PME in this region.

Acknowledgments—We thank M. Ikeda, S. Ito, T. Komagoe, and M. Suzuki for their assistance in the field work and Y. Kawai for the treatment of the coral cores. This work was supported by JSPS KAKENHI grant numbers JP25257207 and JP15H03742068 (PI: TW). U-Th dating was supported by Taiwan ROC MOST (grant numbers 104-2119-M-002-003 and 105-2119-M-002-001) and the National Taiwan University (grant number 105R7625).

References

Abram, N. J., Weber, J. M., Davies, P. J. and Dullo, W. C. (2001) Biological response of coral reefs to sea surface temperature variation: evidence from the raised Holocene reefs of Kikai-jima (Ryukyu Islands, Japan). *Coral Reefs* **20**, 221–234.

Beck, J. W., Edwards, R. L., Ito, E., Taylor, F. W., Recy, J., Rougerie, F., Joannot, P. and Henin, C. (1992) Sea-surface temperature from coral skeletal strontium/calcium ratios. *Science* **257**, 644–647.

Cahyarini, S. Y., Pfeiffer, M., Timm, O., Dullo, W. C. and Schonberg, D. G. (2008) Reconstructing seawater $\delta^{18}O$ from paired coral $\delta^{18}O$ and Sr/Ca ratios: Methods, error analysis and problems, with examples from Tahiti (French Polynesia) and Timor (Indonesia). *Geochim. Cosmochim. Acta* **72**, 2841–2853.

Hu, C., Henderson, G. M., Huang, J., Xie, S., Sun, Y. and Johnson, K. R. (2008) Quantification of Holocene Asian monsoon rainfall from spatially separated cave records. *Earth Planet. Sci. Lett*. **266**, 221–232.

Juillet-Leclerc, A. and Schmidt, G. (2001) A calibration of the oxygen isotope paleothermometer of coral aragonite from *Porites*. *Geophys. Res. Lett*. **28**, 4135–4138.

Lasker, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. and Levrard, B. (2004) A long-term numerical solution for the insolation quantities of the Earth. *Astron Astrophys* **428**, 261–285.

Morimoto, M., Kayanne, H., Abe, O. and McCollouch, M. T. (2007) Intensified mid-Holocene Asian monsoon recorded in corals from Kikai Island, subtropical northwestern Pacific. *Quater. Res*. **67**, 204–214.

Seki, A., Yokoyama, Y., Suzuki, A., Kawakubo, Y., Okai, T., Miyairi, Y., Matsuzaki, H., Namizaki, N. and Kan, H. (2012) Mid-Holocene sea-surface reconstruction using fossil corals from Kume Island, Ryukyu, Japan. *Geochem. J*. **46**, e27–e32.

Shen, C.-C., Wu, C.-C., Cheng, H., Edwards, R. L., Hsieh, Y.-T., Gallet, S., Chang, C.-C., Li, T.-Y., Lam, D. D., Kano, A., Hori, M. and Spotl, C. (2012) High-precision and high-resolution carbonate ^{230}Th dating by MC-ICP-MS with SEM protocols. *Geochim. Cosmochim. Acta* **99**, 71–86.

Sowa, K., Watanabe, T., Kan, H. and Yamano, H. (2014) Influence of Land Development on Holocene *Porites* Coral Calcification at Nagura Bay, Ishigaki Island, Japan. *PLOS ONE* **9**, issue 2.

Sun, Y., Oppo, D. W., Xiang, R., Liu, W. and Gao, S. (2005) Last deglaciation in the Okinawa Trough: Subtropical northwest Pacific link to northern hemisphere and tropical climate. *Paleoceanography* **20**, PA4005, doi:10.1029/2004PA0011061.

Tudhope, A. W., Chilcot, C. P., McCulloch, M. T., Cook, E. R., Chappell, J., Ellam, R. M., Lea, D. W., Lough, J. M. and Shimmield, G. B. (2001) Variability in the El Niño-Southern Oscillation through a Glacial-Interglacial Cycle. *Science* **291**, 1511–1517.

Ujiie, Y., Ujiie, H., Taira, A., Nakamura, T. and Oguri, K. (2003) Spatial and temporal variability of surface water in the Kuroshio source region, Pacific Ocean, over the past 21,000 years: evidence from planktonic foraminifera. *Mar. Micropaleontol*. **49**, 335–364.

Wang, Y. J., Cheng, H., Edwards, R. L., He, Y. Q., Kong, X. G., An, Z. S., Wu, J. Y., Kelly, M. J., Dykoski, C. A. and Li, X. D. (2005) The Holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science* **308**, 854–857.

Watanabe, T., Winter, A. and Oba, T. (2001) Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and ^{16}O/^{18}O ratios in corals. *Mar. Geol*. **173**, 21–35.

Watanabe, T., Suzuki, A., Minobe, S., Kawashima, T., Kameo, K., Minoshima, K., Aguilar, Y. M., Wani, R., Kawahata, H., Sowa, K., Nagai, T. and Kase, T. (2011) Permanent El Nino during the Pliocene warm period not supported by coral evidence. *Nature* **471**, 209–211.

Weber, J. M. and Woodhead, P. M. J. (1972) Temperature dependence of oxygen-18 concentration in reef coral carbonates. *J. Geophys. Lett*. **77**, 463–473.

Wu, W. and Liu, T. (2004) Possible role of the "Holocene Event 3" on the collapse of Neolithic Cultures around the Central Plain of China. *Quater. Int*. **117**, 153–166.

Xiang, R., Sun, Y., Li, T., Oppo, D. W., Chen, M. and Zheng, F. (2007) Paleoenvironmental change in the middle Okinawa Trough since the last deglaciation: Evidence from the sedimentation rate and planktonic foraminiferal record. *Palaeogeography, Palaeoclimatology, Palaeoecology* **243**, 378–393.

SUPPLEMENTARY MATERIALS

URL (http://www.terrapub.co.jp/journals/GJ/archives/data/51/MS482.pdf)
Figures S1 and S2
Table S1