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EXPRESS LETTER

Mid-Holocene sea-surface temperature reconstruction using fossil corals from Kume Island, Ryukyu, Japan

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The relative warmth and stability of the Holocene was punctuated by several brief cold events. Whereas these cold events on a global scale are widely reported, the lack of records from regions such as the East China Sea (ECS) results in an incomplete understanding of the underlying cooling mechanism.
Here, we present a coral-based paleo-SST (sea-surface temperature) reconstruction from the ECS to constrain Holocene variability in the Kuroshio Western Boundary Current and the East Asian Monsoon (EAM). Our new data confirm that cold conditions prevailed at 3.8 cal kyr BP, which is consistent with the previously-reported *Pulleniatina* Minimum Event (PME). While this previous reconstruction could not reveal seasonal differences, our high-resolution data indicate a differing seasonal SST response between summer and winter. This result provides an important insight into understanding the mechanism of the millennium scale cold event in the ECS, the region affected by EAM.

Keywords: Holocene, SST, coral, Sr/Ca, East China Sea

INTRODUCTION

The Holocene (the last 11,700 years) is generally recognized as a relatively stable and warm period, with only minor sea-level excursions (Yokoyama and Esat, 2011). A growing number of studies, however, have reported millennium scale climate perturbations (e.g., Wanner *et al*., 2011; Nakamura *et al*., 2012), but their mechanisms have yet to be fully revealed (Wanner *et al*., 2011). Limitations in the spatial and temporal coverage of paleoclimate data, including the ECS, hinder efforts to reconstruct a globally comprehensive picture of Holocene cold events (Wanner *et al*., 2011).

The climate in the ECS region is influenced by both the East Asian Monsoon and the strength of the Kuroshio Current (Sun *et al*., 2005; Kubota *et al*., 2010). The East Asian Summer Monsoon (EASM) transports significant amounts of moisture to continental Asia and affects human activity through changing vegetation and water supply (Yokoyama *et al*., 2011), while the East Asian Winter Monsoon (EAWM) brings cold wind under the effect of the Siberian High. The Kuroshio transfers a large heat flux from the ocean to the atmosphere and is thus of significant interest in climatological contexts.

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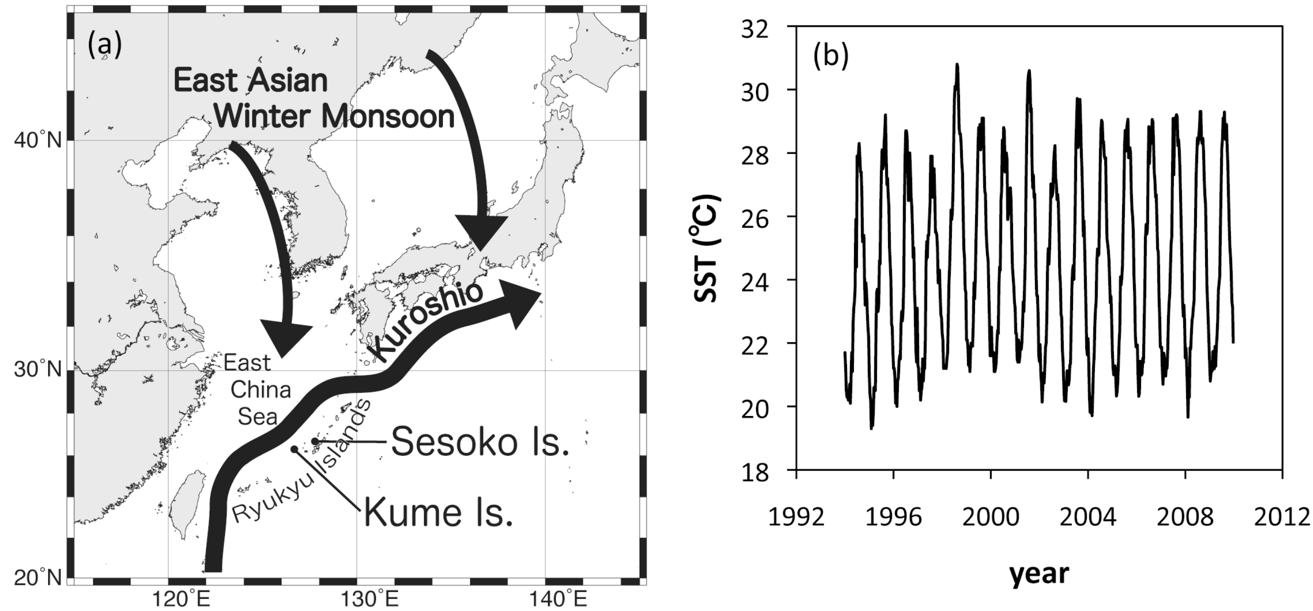

Fig. 1. (a) Study sites, Kume and Sesoko Island of the Ryukyu Islands and the East Asian Winter Monsoon system. The arrows show winter monsoon wind and Kuroshio Current. (b) Observed SST in Motobu port, near Sesoko Island.

Several studies have reconstructed paleo-SST in the ECS and suggested that millennial-scale cold events are manifested during the Holocene (e.g., Sun *et al*., 2005; Xiang *et al*., 2007). They use proxies such as oxygen isotopes, Mg/Ca-based SST reconstruction, and faunal analysis of planktonic foraminifera. The number and timing of cold events are varied, depending on reconstructions. The major cold event recognized in this region is known as the *Pulleniatina* Minimum Event (PME, 4.5–3.0 ka), which is related to weakening of the Kuroshio influence (Ujiié and Ujiié, 1999). However, previous reconstructions were unable to reveal seasonal-scale variations. The EAM effects on the ECS climate differ between summer and winter. Therefore, seasonal climate reconstructions are necessary to reveal details of ECS paleoclimate variability.

Coral exhibits annual bandings and a rapid growth rate that enables reconstruction of paleoclimate at seasonal time scales. Among the various chemical components in coral skeletons, Sr/Ca ratios are a reliable proxy for SST (e.g., Beck *et al*., 1992; Corrège, 2006). Previous SST reconstructions based on Sr/Ca for ECS during the Holocene are limited to Kikai Island and targeted two time windows, at 6180 cal yr BP and 7010 cal yr BP (Morimoto *et al*., 2007). This is insufficient to reconstruct paleoclimate in the ECS, and further data that greatly expand the temporal range are required to better understand the global relationship with other climate archives.

In this study, we reconstruct mid- to late-Holocene SST using fossil and modern corals from Kume and Sesoko islands, by applying Sr/Ca measurements to understand SST in the ECS at seasonal time scales. Our coral record confirmed the major cold event, PME, and revealed seasonal differences during this interval.

Materials and Methods

The study site, Kume Island is located in the Ryukyu Islands, on the southeast side of the ECS (Fig. 1a). Two fossil *Porites* spp. corals (KSR-10-20, KSR-10-21) were collected from the southwest coast of Kume Island in 2010. The fossil corals were sliced, and radiocarbon dates were determined using AMS.

We conducted XRD and SEM analyses to check the quality of the corals, and the two specimens proved to be pristine. Microsampling was conducted and the powders were then weighed (100 ± 5 μg each) prior to dissolution in 5 ml of 2% HNO_3 (Suzuki *et al*., 2003). Both Ca and Sr concentrations were measured by ICP-AES (Mishima *et al*., 2009). Reproducibility of the JCp-1 standard (Okai *et al*., 2002) was 0.4% (2σ).

Two modern corals (SES04-31-A5, SES04-05-A3) were collected in 2004 from Sesoko Island, which is located 110 km east of Kume Island (Fig. 1a). Sr/Ca ratios were measured to provide modern SST as a counterpart to the fossil corals taken from Kume Island, since they are in the same SST region according to satellite data (IGOSS, 1° grid). Our Sr/Ca-SST equation is established in a similar way to that employed by Morimoto *et al*. (2007), using the SST data collected by the Japan Ocea-

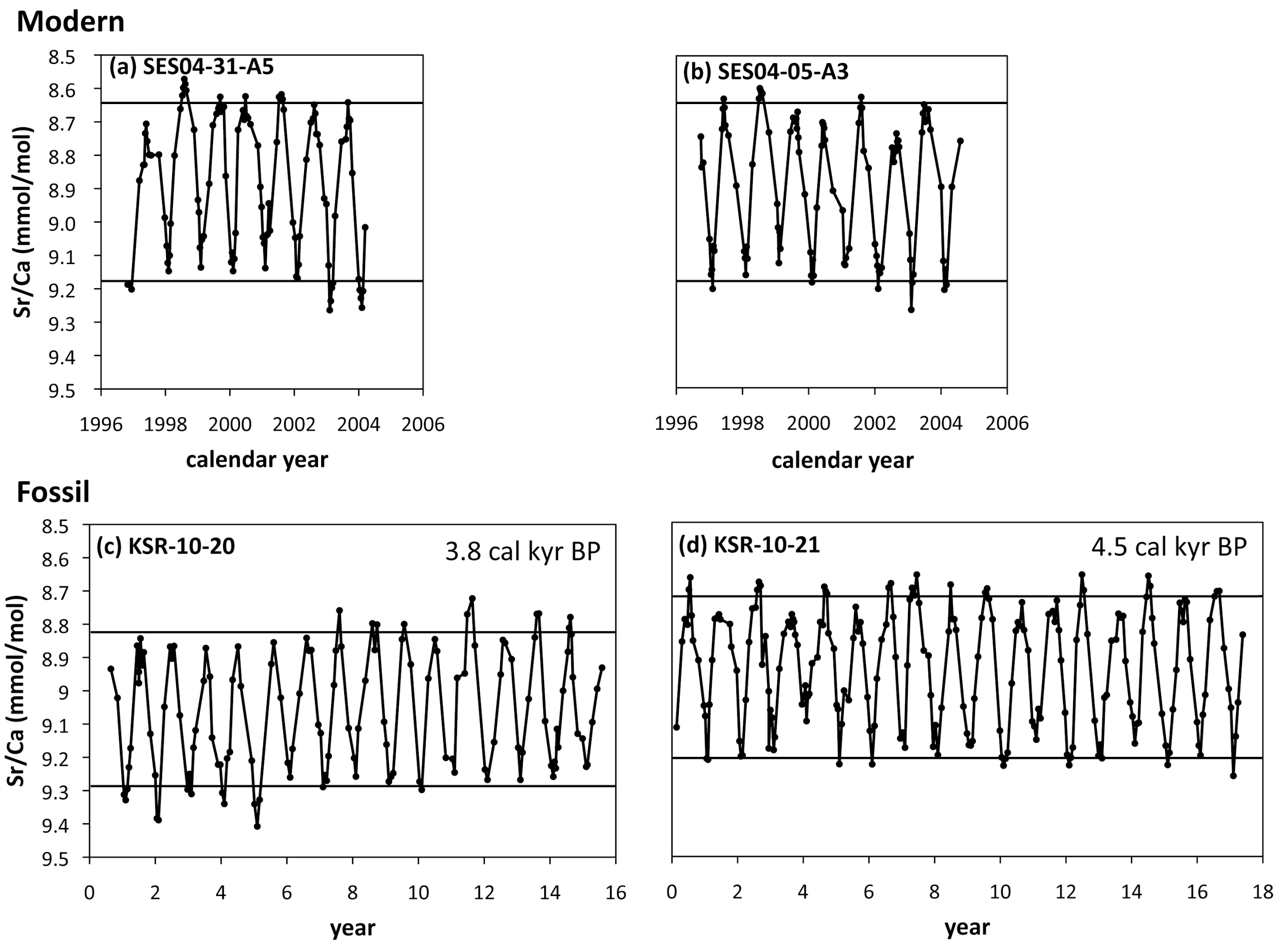

Fig. 2. (a), (b) Sr/Ca ratios of modern corals. SES04-31-A5 has the record from summer in 1997 to winter in 2004. SES04-05-A3 has the record from winter in 1997 to winter in 2004. (c) Sr/Ca ratio of fossil coral KSR-10-20. The age of this specimen is 3.8 cal kyr BP, and it has the annual records of 15 years. (d) Sr/Ca ratio of fossil coral KSR-10-21. The age of this specimen is 4.5 cal kyr BP, and it has the annual records of 17 years. Solid lines show summer and winter peak averages in each coral.

nographic Data Center at Motobu port, located within 1 km from the sampling sites (Fig. 1b).

Results and Discussion

Figure 2 and Table 1 show the results of Sr/Ca analysis. The average Sr/Ca ratios of the two modern corals are approximately identical during both summer and winter (Figs. 2a and 2b). The growth rates of two modern corals were 12 mm/yr and 16 mm/yr, and the 400 μm sampling interval corresponds to approximately 10 days. Thus we used 10 days average of modern SST data to reconstruct the Sr/Ca vs. SST equation.

Obtained relations of Sr/Ca and SST for the two modern corals are virtually identical. Therefore, we combined the two equations, to give: Sr/Ca (mmol/mol) = 10.440–0.0611 SST (°C) ($r^2 = 0.981$, $P < 0.01$, Fig. 3a). This is robust, since the slope is similar to the one that was obtained previously from averaging the 37 reported equations for *Porites* spp. (Corrège, 2006).

Radiocarbon dates were converted to calendar ages using Marine09 (Reimer *et al.*, 2009) with $\Delta R = 29 \pm 18$ (Yoneda *et al.*, 2007), and they are respectively 3785 ± 85 and 4495 ± 95 cal yr BP. We estimated paleo-SST by applying the Sr/Ca vs. SST equation established for modern corals, and found that summer and winter SST are 26.5°C and 18.7°C respectively at 3.8 cal kyr BP, while those at 4.5 cal kyr BP are 28.4°C and 20.4°C (Table 1).

To seek the natural variability in SST, we needed to correct the modern SST value for recent global warming, given that annual SST in the study area during the 20th century has gradually increased by a rate of 1.12 ± 0.18°C (JMA, 2012). This trend also persisted for seasonal SST during the past 100 years, at 0.65 ± 0.21°C and 1.41 ± 0.30°C respectively for summer and winter (JMA, 2012). These were removed from the observed SST and the

Table 1. The Sr/Ca ratios and calculated SST

Sr/Ca (mmol/mol)	SES04 modern	KSR-10-20 3.8 cal kyr BP	KSR-10-21 4.5 cal kyr BP
Summer min.	8.65	8.82	8.71
Winter max.	9.18	9.29	9.20
Annual	8.91	9.06	8.95
Seasonality	0.54	0.48	0.49

Temperature (°C)	Motobu port, observed SST	Calculated SST pre-industrial	Sr/Ca-based SST 3.8 cal kyr BP	Sr/Ca-based SST 4.5 cal kyr BP
Summer	29.3	28.7	26.5	28.4
Winter	20.6	19.2	18.7	20.4
Annual	25.0	23.8	22.6	24.4
Seasonality	8.7	9.5	7.8	8.0

Note: The summer and winter Sr/Ca ratios are averages of seasonal extremes of coral Sr/Ca ratio record and also shown in Fig. 2.

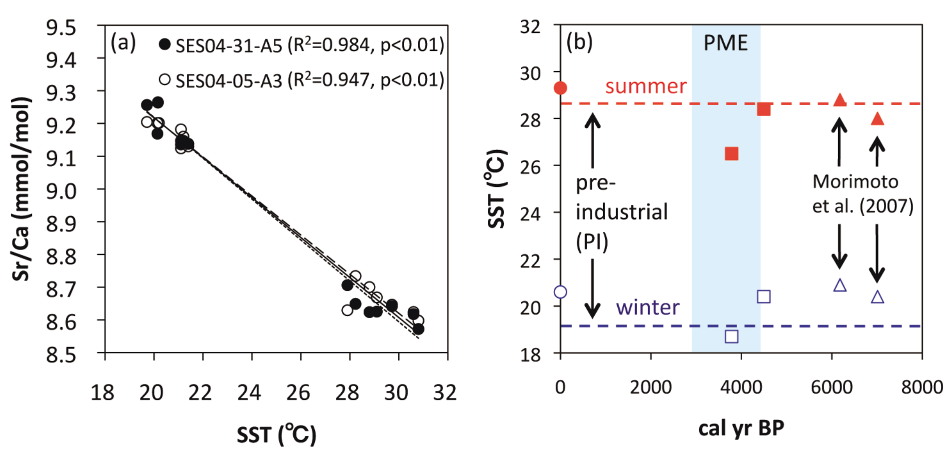

Fig. 3. (a) The relation of modern coral Sr/Ca ratio and observed SST. Dashed lines represent regression lines for each coral. The solid line represents the combined regression line. There is little difference between the regression lines of the two modern corals. Sr/Ca-SST equations in two corals are Sr/Ca (mmol/mol) = 10.469–0.0625 SST (°C) (r^2 = 0.984, $P < 0.01$) for SES04-31-A5, and Sr/Ca (mmol/mol) = 10.271–0.0538 SST (°C) (r^2 = 0.947, $P < 0.01$) for SES04-05-A3. Because of their similarity, we used a combined equation for calculation of past SST. (b) Coral Sr/Ca-SST in Kume Island obtained in this study (square) and coral Sr/Ca-based SST in Kikai Island (Morimoto et al., 2007) (triangle). Observed SST in Motobu port (circle) and pre-industrial SST (extracted effect of recent global warming from Motobu observed SST) (dashed line) are also shown. Summer SSTs are shown in filled (red) symbols, and winter SSTs are open (blue) symbols. The period corresponding to PME is also shown.

detrended result is referred to as the "pre-industrial" (PI) SST. Summer SST, at 3.8 cal kyr BP, was 2.2°C lower than PI SST, whereas winter SST at 4.5 cal kyr BP was 1.2°C higher. No significant differences were found for winter SST at 3.8 cal kyr BP and summer SST at 4.5 cal kyr BP, compared to PI SST in the ECS (Fig. 3b, Table 1).

Present day temperatures, both in Kikai and Kume Islands are identical (approximately 0.1°C in summer and 0.7°C in winter, from recent 30 year's IGOSS SST data), due to the Kuroshio trajectory, and SST during the interval of 7–4.5 cal kyr BP exhibits stability. However, significantly lower SST, both in summer and in winter, can be recognized at 3.8 cal kyr BP in the area (Fig. 3b).

The PME (Ujiié and Ujiié, 1999) is the major cold event among several millennial-scale cold events reported to have occurred during the Holocene in the ECS. During the PME, the abundance of the planktonic foraminifer *Pulleniatina obliquiloculata*, typically found in Kuroshio water, abruptly decreased in deep-sea sedimentary cores, and this was interpreted as a possible weakening of the Kuroshio current (Ujiié and Ujiié, 1999; Ujiié *et al.*, 2003). This cold event has been reported in many other previous studies, not only from faunal assemblage of planktonic foraminifera, but also from foraminiferal Mg/Ca-based SST reconstructions (e.g., Li *et al.*, 1997; Xiang *et al.*, 2007). However, Lin *et al.* (2006) concluded that there was no such change either in SST or SSS during the Holocene, from their foraminifer based reconstruction. Thus the PME is still controversial. In this study, cooling episodes found in fossil corals (Fig. 3b) coincided with the PME both in summer and winter. This is evidence for the existence of the PME during the mid Holocene, and the magnitude of SST decrease compared to PI is –2.2°C in summer and –0.5°C in winter (Fig. 3b). In addition, previously reported timing of the PME, both starting and ending, varied from 4.6 ka to 4 ka and from 3 ka to 2 ka, respectively. Our results confirm that the PME started after 4495 ± 95 cal yr BP and ended after 3785 ± 85 cal yr BP.

Since mechanisms of millennium scale cold events have not been identified, these results provide important insights for understanding the mechanism of paleoclimate in the ECS. Seasonal reconstructions of SST are particularly useful, since climate in the ECS is affected not only by the Kuroshio current, but also by the EAM. Because the EAM influences differ between summer and winter, the different degree of decreased SST reconstructed in this study for 3.8 cal kyr BP may possibly have been caused by a change in seasonal intensity of the EAM. Further coral based studies are necessary to provide strong constraints on understanding the mechanisms of cold events in the ECS, providing seasonal scale SST for many other time windows.

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