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NOTE

Stable oxygen isotope records of corals and a sclerosponge in the Western Pacific warm pool

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Abstract High-resolution measurements of the stable oxygen isotopic signature ($\delta^{18}O$) of two new 10-year *Porites lobata* coral cores and one previously studied multi-decadal sclerosponge *Acanthocheatetes wellsi* from the Republic of Palau (7°16′N, 134°31′E) located in the Western Pacific warm pool were analyzed and monthly interpolated time-series records developed. Despite significant differences in collection depth and growth rates, both coral and sclerosponge faithfully recorded the interannual changes of sea surface salinity (SSS) driven by the strong influence of the El Niño Southern Oscillation (ENSO). The strong relationship of coral skeletal $\delta^{18}O$ with SSS, but not sea surface temperature or precipitation, confirms previous findings that changes in Palau regional surface water are driven by the advection of water masses into the area over interannual timescales associated with ENSO. Opportunities exist for the expansion of short coral proxy records with longer sclerosponge records to verify the stability of ENSO-induced SSS variability over longer timescales.

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Introduction

The skeletal $\delta^{18}O$ [$\delta^{18}O$ = per mil deviation of ^{18}O:^{16}O relative to Vienna Peedee Belemnite] of healthy corals (growth rates of 1–2 cm per year, e.g., Druffel 1997; Grottoli and Eakin 2007) and sclerosponges (growth rates of 0.01–2.3 mm per year, e.g., Willenz and Hartman 1989; Fallon and Guilderson 2005; Grottoli 2006) have been proven to be reliable recorders of sea surface temperature (SST) and sea surface salinity (SSS) variability (e.g., Dunbar et al. 1994; Wellington et al. 1996; Swart et al. 2002; Rosenheim et al. 2004; Asami et al. 2005). Skeletal $\delta^{18}O$ signatures of corals and sclerosponges are influenced by temperature-dependent fractionation (Epstein et al. 1953; Kim and O'Neil 1997) and the $\delta^{18}O$ of seawater that is directly related to changing seawater salinity (Cole and Fairbanks 1990; Fairbanks et al. 1997).

In regions of low SSS variability, coral and sclerosponge skeletal $\delta^{18}O$ are primarily recorders of SST (e.g., Wellington et al. 1996; Rosenheim et al. 2004). In locations such as the Western Pacific warm pool (WPWP) with low SST variability, skeletal $\delta^{18}O$ is primarily a recorder of SSS (Morimoto et al. 2002; Asami et al. 2005; Iijima et al. 2005) influenced by the El Niño Southern Oscillation (ENSO)-driven interannual variability of SSS (Delcroix et al. 1996; Fig. 1a, b). In the WPWP, evaporation and precipitation are enhanced by the consistently high SST, by the seasonal migration of the intertropical convergence zone (ITCZ), and by the influence of ENSO on the position of both the ITCZ and the SST.

Here, new 10-year (1993–2003) high-resolution $\delta^{18}O$ records from two coral colonies in the WPWP (Republic of Palau, 7°16′N, 134°31′E) are presented and extended to 1988 by overlapping them with a sclerosponge skeletal $\delta^{18}O$ record. The composite $\delta^{18}O$ record (coral and sclerosponge) was compared to instrumental SST, SSS, and precipitation data, as well as the Southern Oscillation Index (SOI) to investigate the sensitivity of this carbonate geochemical signal to environmental variables. This study presents the first multi-species composite carbonate time-series, demonstrating the potential to temporally extend climate proxy data. This extended $\delta^{18}O$ record supports previous findings that coral $\delta^{18}O$ is driven by salinity changes related to ENSO in the WPWP.

Materials and methods

In July 2003, two *Porites lobata* cores (H2 and H4) were collected within 20 m of each other at 2–3 m depth at Short Drop Off (7°16′N, 134°31′E) on the eastern coast of Palau in the WPWP (Fig. 1c). Short Drop Off (Fig. 1d) is a 100 m

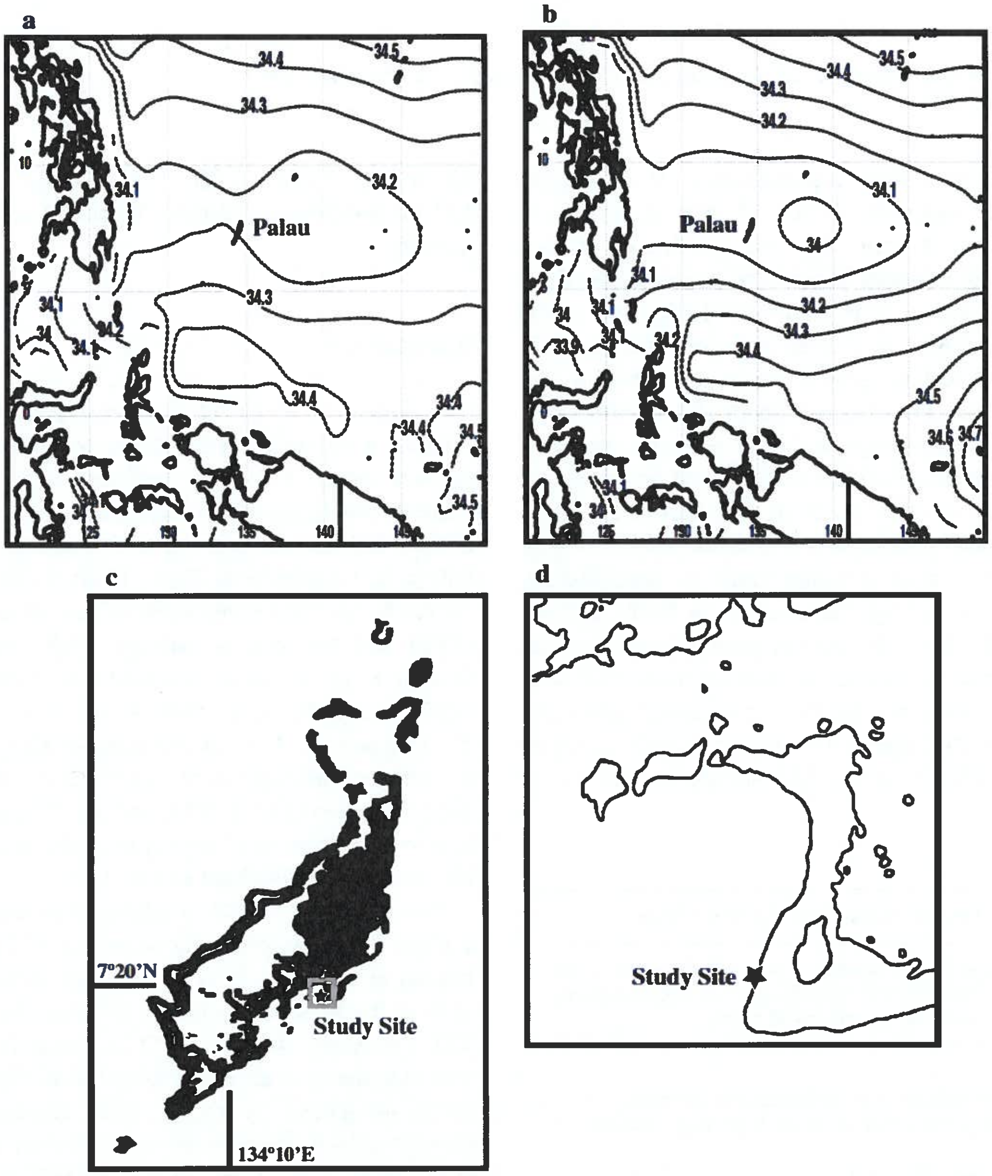

Fig. 1 Averaged regional sea surface salinity (*SSS*) contours in the uppermost 20 m from 1971 to 2005 derived from data in Ishii et al. (2006) during a El Niño and **b** La Niña periods. **c** Republic of Palau (7°16′N, 134°31′E) with a close-up box of the coral collection site at **d** Short Drop Off. El Niño (La Niña) periods correspond to positive (negative) anomalies of NOAA Climate Prediction Center (*CPC*)—Southern Oscillation Index (*SOI*; www.cpc.noaa.gov/data/indices/) and the Oceanic Niño Index (*ONI*; www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtm)

deep reef wall located 2 km offshore experiencing open ocean conditions with no known influence of terrestrial sources (Grottoli 2006). Sample collection and analytical methodologies of the two coral colonies' skeletal $\delta^{18}O$ signatures were performed according to well-established methods that are summarized in the electronic supplementary material (ESM) section. One sclerosponge colony, *Acanthocheatetes wellsi*, was collected at 17 m depth in July 2001 at the same location with detailed descriptions of methodologies reported in Grottoli (2006). Replicated monthly coral $\delta^{18}O$ skeletal time-series from 1995 to 2003 and an extended skeletal $\delta^{18}O$ composite record from 1988 to 2003 (coral $\delta^{18}O$ plus sclerosponge $\delta^{18}O$ records) were compared to regional environmental variables of SST, SSS, precipitation, and SOI as described in the ESM.

Results and discussion

Coral $\delta^{18}O$ records

Core H2 displayed clear banding with an average extension rate of 10.44 mm year^{-1}. H4's banding was not as clear, and the calculated extension rate of 12.57 mm year^{-1} was less reliable (Fig. S1). Both coral $\delta^{18}O$ records were within analytical error of each other (mean $\delta^{18}O \pm 1$ standard deviation for H2 = −5.59‰ ± 0.16 and H4 = −5.62‰ ± 0.16). While large differences in skeletal growth rate can affect $\delta^{18}O$-based temperature and/or salinity reconstructions in *Porites* corals (McConnaughey 1989; Gagan et al. 1994; Allison et al. 1996; Cohen and Hart 1997; Felis et al. 2003), moderate differences along the major axis of growth has no effect on skeletal $\delta^{18}O$ in healthy mounding corals (Grottoli and Wellington 1999). The slight difference in growth rates observed here was assumed to have had no significant influence on the interpretation of the $\delta^{18}O$ records. Based on the developed age model, the 100 mm of growth spanned the periods of November 1993–July 2003 (H2) and June 1995–July 2003 (H4) with each $\delta^{18}O$ mm sample representing ~5 and ~4 weeks of growth in cores H2 and H4, respectively.

Visually, the interannual variability of both centered monthly coral $\delta^{18}O$ records appeared to be similar (Fig. 2), though statistically only 26% of the variance between the cores was explained by the correlation between the two cores (Table 1). By averaging the two centered records, the variation in either single record due to genotypic differences was minimized and the signal-to-noise ratio increased (i.e., Lough 2004; Grottoli and Eakin 2007) to produce a more robust oceanographic proxy.

Skeletal $\delta^{18}O$ and environmental records

Both short coral $\delta^{18}O$ records (Fig. 2) and the sclerosponge (Fig. 3; Grottoli 2006) $\delta^{18}O$ record displayed enrichment/depletion during El Niño (EN)/La Niña (LN) events. This was supported by the significant relationship between the average coral and composite coral–sclerosponge $\delta^{18}O$ records with SOI (Table 1). The annual variation was relatively subdued, with almost no seasonal variation. Since SSS does not vary to any significant degree in the WPWP on monthly or seasonal timescales (Delcroix et al. 2005), it is not surprising that skeletal $\delta^{18}O$ also does not have a monthly or seasonal signal. More interestingly, even though the two species were growing at different depths with significantly different growth rates, similar patterns of skeletal $\delta^{18}O$ variability (Fig. 3) over the replicated period of ~1995–2001 illustrate that the two marine organisms recorded similar regional climate variability.

Neither averaged in situ SST measurements nor IGOSS SST showed SST as the primary driving force of skeletal $\delta^{18}O$ variability in corals or the composite coral–sclerosponge

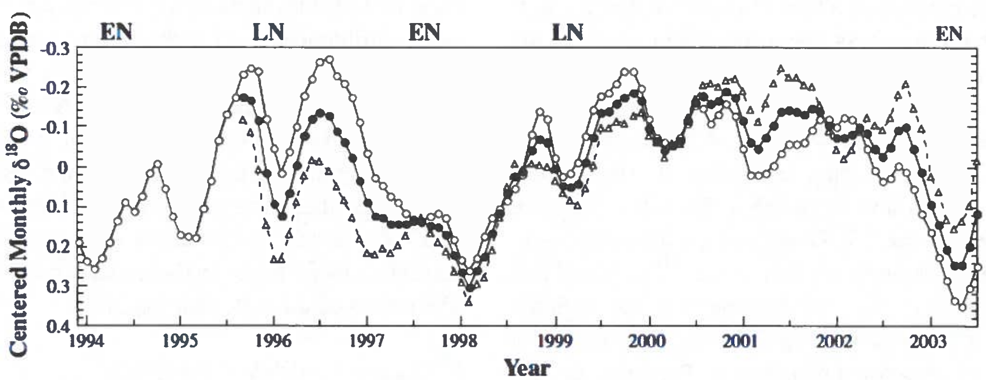

Fig. 2 Interpolated monthly $\delta^{18}O$ of corals H2 (*open circle*; Nov. 1993–Jul. 2003), H4 (*open triangle*; Jun. 1995–Jul. 2003), and averaged coral (*filled circle*; Jun. 1995–Jul. 2003), all centered about the mean skeletal $\delta^{18}O$ of each respective time-series, shown here with 3-month running mean. El Niño (*EN*)/La Niña (*LN*) episodes are denoted above the figure as defined by NOAA CPC-ONI and SOI

Table 1 Statistical results of covariance (coefficients of determination R^2 values, where bracketed values indicate statistical significance at $P < 0.01$) between monthly environmental variables and coral colonies (1992–2003), sclerosponge (1988–2001; Grottoli 2006), and the composite record (1988–2003)

	Coral H2 $\delta^{18}O$	Coral H4 $\delta^{18}O$	Average Coral $\delta^{18}O$	Sclerosponge $\delta^{18}O$	Composite $\delta^{18}O$	IGOSS SST	In situ SST	Blended SSS	Precipitation	SOI
Coral H2 $\delta^{18}O$	–	[0.26]	[0.74]	–	–	[0.20]	[0.15]	[0.26]	0.05	[0.40]
Coral H4 $\delta^{18}O$	[0.26]	–	[0.76]	–	–	[0.15]	0.02	[0.18]	[0.08]	[0.17]
Average Coral $\delta^{18}O$	[0.74]	[0.76]	–	–	–	[0.19]	0.09	[0.40]	[0.09]	[0.36]
Sclerosponge $\delta^{18}O$	–	–	–	–	–	0.008	–	0.03	0.001	[0.25]
Composite $\delta^{18}O$	–	–	–	–	–	[0.11]	0.09	[0.17]	0.02	[0.33]
IGOSS SST	[0.20]	[0.15]	[0.19]	0.008	[0.11]	–	[0.81]	0.04	0.05	[0.17]
In situ SST	[0.15]	0.02	0.09	–	0.09	[0.81]	–	0.11	0.05	[0.37]
Blended SSS	[0.26]	[0.18]	[0.40]	0.03	[0.17]	0.04	0.11	–	0.02	[0.08]
Precipitation	0.05	[0.08]	[0.09]	0.001	0.02	[0.05]	0.05	0.02	–	[0.07]
SOI	[0.40]	[0.17]	[0.36]	[0.25]	[0.33]	[0.17]	[0.37]	[0.08]	[0.07]	–

Gridded IGOSS sea surface temperature (SST) from Reynolds and Smith (1994) and Reynolds et al. (2002) with additional in situ SST provided by Mr. Theo Isamu of Palau's Bureau of Natural Resources. Sea surface salinity (SSS) data provided by blending in situ collected measurements from Morimoto et al. (2002) for the period of February 1998 to July 2000 combined with the monthly estimated SSS values of Iijima et al. (2005) for the period of January 1988 to March 1998. Precipitation data provided by *NOAA* National Climatic Data Center (NCDC)—Koror Station (http://www7.ncdc.noaa.gov/IPS/lcd/lcd.html?_page=1&state=PI&stationID=40309&_target2=Next+%3E). Southern Oscillation Index (SOI) provided by NOAA's indices site (http://www.cpc.noaa.gov/data/indices/). Composite $\delta^{18}O$ = Combined average coral and sclerosponge $\delta^{18}O$ record

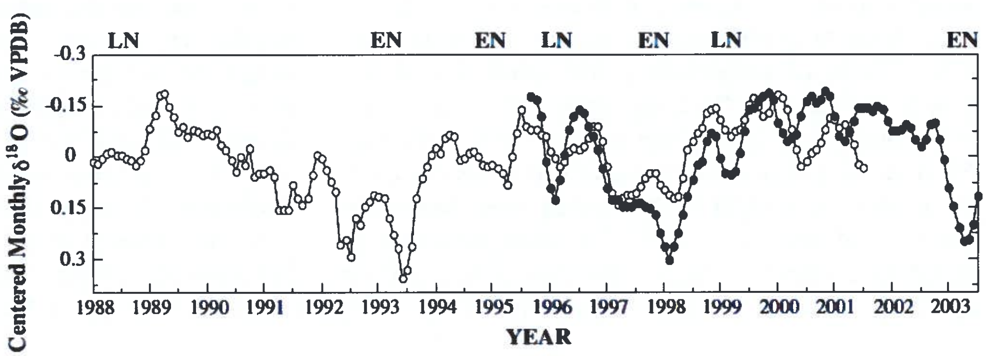

Fig. 3 Centered monthly average coral $\delta^{18}O$ record (*filled circle*) with monthly $\delta^{18}O$ anomaly of a sclerosponge from Grottoli (2006) (*open circle*). El Niño (*EN*)/La Niña (*LN*) episodes are denoted above defined by NOAA CPC-ONI and SOI

record (Table 1; Fig. 4a). To further illustrate this point, if skeletal $\delta^{18}O$ variability was due to temperature alone, the composite coral–sclerosponge $\delta^{18}O$-based reconstructed SST record would produce an unrealistic warming of 2.4°C compared to the IGOSS SST warming of 1°C from 1989 to 1994 and a ~0.1°C warming compared to the IGOSS warming of ~0.5°C from 1988 to 2003. The low covariance between the average coral $\delta^{18}O$ and precipitation and insignificant correlation between the composite $\delta^{18}O$ record and precipitation (Table 1; Fig. 4b) indicate that the region's surface water $\delta^{18}O$ was not significantly influenced by ENSO-driven evaporation–precipitation regimes in the region. Finally, interannual variation of in situ SSS (Morimoto et al. 2002) and estimated SSS (Iijima et al. 2005) shown as a blended dataset significantly increased as average coral $\delta^{18}O$ values increased (3-month lag, due to slight age model differences from multiple time-series, Fig. 4c). Both the average coral skeletal $\delta^{18}O$ record and the composite carbonate $\delta^{18}O$ record increase as SSS increases with a covariance of 0.40 and 0.17, respectively (Table 1). As such, SSS is the greatest predictor of skeletal $\delta^{18}O$ variability of all of the examined environmental variables, with the greatest sensitivity in the coral relative to the sclerosponge record. The relationship between the average coral $\delta^{18}O$ record and SSS produced the following equation:

$$\delta^{18}O_{coral} = -10.549 + 0.14(SSS)$$

The vertical SST profiles of the top 35 m over a ~10 year period displayed thorough mixing at all times

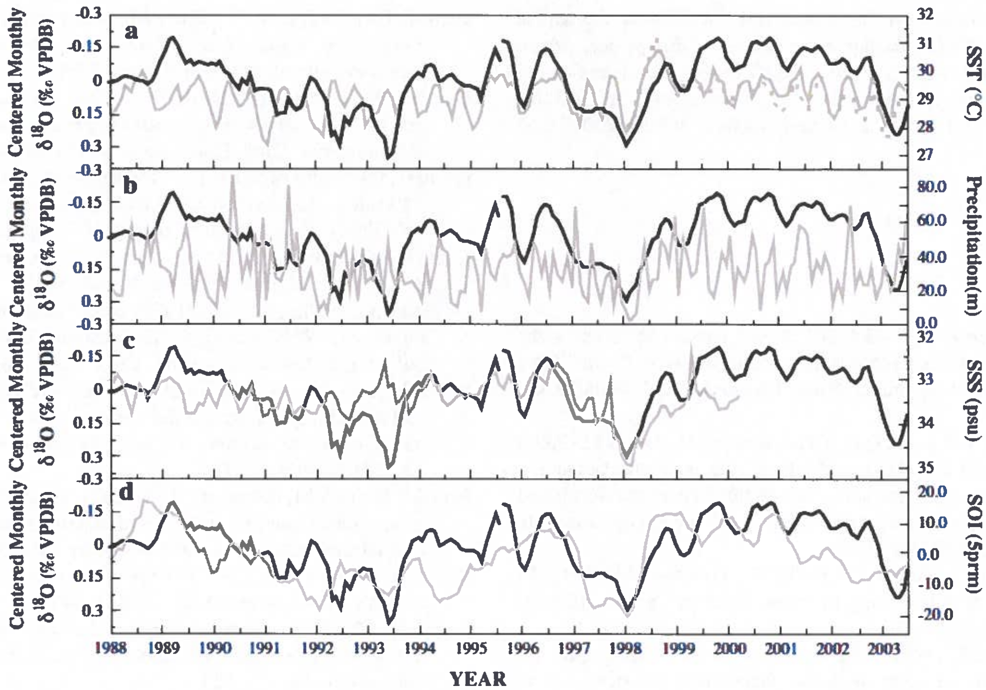

Fig. 4 The coral $\delta^{18}O$ record from 1995 to 2003 (*black*) extended with the sclerosponge $\delta^{18}O$ record (*black*) from 1988 to 1995 compared against a 1988–2003 monthly IGOSS SST (*gray*) verified with 1998–2003 mean in situ SST dataset (*dashed gray*) acquired from three independent submersible hourly temperature loggers (*HOBO*), **b** precipitation (*gray*) from 1988 to 2003, **c** blended monthly in situ sea surface salinity measurements from Morimoto et al. (2002) and reconstructed SSS estimates from Iijima et al. (2005) (*gray*) ending at 2000, and **d** 1988–2003 monthly SOI (*gray*)

including during ENSO events (Colin, pers. comm.). The similarity in both the coral (2–3 m depth) and the sclerosponge (17 m depth) $\delta^{18}O$ records suggests that SSS is equally well mixed in at least the top 17 m.

The strength of the covariance between skeletal $\delta^{18}O$ and SSS is far stronger than that of the covariance of skeletal $\delta^{18}O$ with either precipitation or SST. Thus, it was deduced that the changes in Palau regional surface water were predominantly influenced by SSS variability driven by the advection of water masses into the area over interannual timescales associated with ENSO, and not by local precipitation and SST changes.

Skeletal $\delta^{18}O$ and historical ENSO

Average coral and sclerosponge skeletal $\delta^{18}O$ significantly increased as monthly SOI anomalies decreased (Table 1; Fig. 4d). These findings agree with previous coral (Morimoto et al. 2002; Iijima et al. 2005) and sclerosponge (Grottoli 2006) studies from this region, which showed that skeletal $\delta^{18}O$ records in Palau are sensitive to strong SOI events over interannual timescales, driven by changes in regional SSS. Thus, it was not surprising that both the corals and the sclerosponge recorded similar ENSO-driven $\delta^{18}O$ variability indicating that sclerosponge records could be used to extend coral records further back in time.

The moderate EN event of 2002/2003 appeared to elicit a similar enrichment response in the coral $\delta^{18}O$ records as the severe 1997/1998 EN event. One possible explanation could be that while regionally the 2002/2003 event was moderate, locally it was similar in severity to the 1997/1998 event as evidenced by the similar minimum SST values of ~27.5°C in early 1998 and 2003 in both the in situ and the IGOSS SST data. Alternatively, it is possible that a slight growth hiatus in the corals related to the documented widespread bleaching in the region, which occurred during the 1997/1998 event (Bruno et al. 2001), underestimating the event intensity. However, this latter scenario was unlikely since the skeletal extension rates were not very different from non-EN years.

The two marine organisms' skeletal $\delta^{18}O$ show great promise in recording SSS variability driven by ENSO over interannual timescales tracking the SOI. Longer sclerosponge records may provide the potential to extend shorter coral-based proxy records thus enabling study of the relationship between SSS and SOI over longer timescales.

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