Invited Research Papers

Coral-based proxy calibrations constrain ENSO-driven sea surface temperature and salinity gradients in the Western Pacific Warm Pool

Ahmad T. Mohtar, Konrad A. Hughen, Nathalie F. Goodkin, Iulia-Madalina Streanga, Riovie D. Ramos, Dhrubajyoti Samanta, James Cervino, Adam D. Switzer

Asian School of the Environment, Nanyang Technological University, Singapore
Earth Observatory of Singapore, Nanyang Technological University, Singapore
Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, United States
Department of Earth and Planetary Sciences, American Museum of Natural History, United States
Department of Environmental Sciences, William Paterson University, United States
Restoration and Conservation Advisement, United States

ARTICLE INFO

Keywords:
Sr/Ca
δ¹⁸Osw
Porites spp.
ENSO
Spatial index
Multi-timescale calibration

ABSTRACT

Constraining past variability in ocean conditions in the Western Pacific Warm Pool (WPWP) and examining how it has been influenced by the El-Niño Southern Oscillation (ENSO) is critical to predicting how these systems may change in the future. To characterize the spatiotemporal variability of the WPWP and ENSO during the past three decades, we analyzed climate proxies using coral cores sampled from Porites spp. from Kosrae Island (KOS) and Woleai Atoll (WOL) in the Federated States of Micronesia. Coral skeleton samples drilled along the major growth axis were analyzed for oxygen isotopes (δ¹⁸Oc) and trace element ratios (Sr/Ca), used to reconstruct sea surface salinity and temperature (SSS and SST). Pseudocoral δ¹⁸O time series (δ¹⁸Opseudo) were calculated from gridded instrumental observations and compared to δ¹⁸Oc, followed by fine-tuning using coral Sr/Ca and gridded SST, to produce age models for each coral. The thermal component of δ¹⁸Oc was removed using Sr/Ca for SST, to derive δ¹⁸O of seawater (δ¹⁸Osw), a proxy for SSS. The Sr/Ca, and δ¹⁸Osw records were compared to instrumental SST and SSS to test their fidelity as regional climate recorders. We found both sites display significant Sr/Ca-SST calibrations at monthly and interannual (dry season, wet season, mean annual) timescales. At each site, δ¹⁸Osw also exhibited significant calibrations to SSS across the same timescales. The difference between normalized dry season SST (Sr/Ca) anomalies from KOS and WOL generates a zonal SST gradient (KOSWOLSST), capturing the east-west WPWP migration observed during ENSO events. Similarly, the average of normalized dry season δ¹⁸Osw anomalies from both sites produces an SSS index (KOSWOLSSS) reflecting the regional hydrological changes. Both proxy indices, KOSWOLSST and KOSWOLSSS, are significantly correlated to regional ENSO indices. These calibration results highlight the potential for extending the climate record, revealing spatial hydrological gradients within the WPWP and ENSO variability back to the end of the Little Ice Age.

1. Introduction

El Niño-Southern Oscillation (ENSO) is the most dominant coupled mode of tropical climate variability that is known to affect global climate through teleconnections (Bjerknes, 1969; Rasmussen and Carpenter, 1982; Cane, 1986; Philander, 1990; Trenberth, 1997; Wallace et al., 1998; Thompson et al., 2006; Santos et al., 2017; Timmermann et al., 2018). Changes in intensity and frequency of ENSO events (i.e. El Niño and La Niña) are known to cause extreme weather conditions (McPhaden et al., 2006), impacting human health (McKibben et al., 2017; Anyamba et al., 2019; Lam et al., 2019), infrastructure (Brakenridge et al., 2017; Giuliani et al., 2019) and food security (Williams and Funk, 2011; Anderson et al., 2019). However, the predictability of ENSO events remains challenging due in part to our incomplete knowledge of the full range of spatiotemporal natural behavior of ENSO (Lu et al., 2018). Our limited understanding of long
Changes in the WPWP are therefore reflective of the intensity and location of El Niño events (Singh et al., 2011; Capotondi et al., 2015; Qi et al., 2019). Walker Circulation and ENSO. Our limited knowledge of spatio-temporal ENSO variability may appear differently depending on location in the eastern, central or western Pacific (Li et al., 2011; Nurhati et al., 2011; Partin et al., 2013; Yamoah et al., 2016; Shi and Wang, 2019). Some studies rely on teleconnections to distant regions (Moy et al., 2002; Schöngart et al., 2004; D’Arrigo et al., 2005; Räisänen et al., 2016; Stahle et al., 2016), whereas Pacific corals provide high-resolution records of hydrographic variability within ENSO’s spatial footprint. However, only a limited number of studies in the Western Pacific Warm Pool (WPWP) extend beyond 100–200 years to constrain long-term ENSO variability (e.g., Tudhope et al., 1995; McGregor and Gagan, 2004; Linsley et al., 2006; Quinn et al., 2006; Gorman et al., 2012; Osborne et al., 2014), a key region concerning the Walker Circulation and ENSO. Our limited knowledge of spatio-temporal ENSO behavior over long timescales results in significant uncertainties in modelling ENSO within general circulation models (GCMs) (Wittenberg, 2009; Schmidt et al., 2011; Newman et al., 2018). These challenges in modelling ENSO are exacerbated by the mean-state model biases such as, westward extended sea surface temperature (SST) variability and double inter Tropical Convergence Zone (ITCZ) in the state-of-the-art GCMs over WPWP (Samanta et al., 2018; Samanta et al., 2019).

The WPWP, defined as the region with mean annual SST above 28°C typically between 15°S-15°N, 120°E-160°W, forms when the trade winds transport warm water across the tropical Pacific to the western boundary formed by the Maritime Continent (Wyrkti, 1974; Enfield et al., 2006). The WPWP then feeds the western boundary currents delivering heat from the tropics to the sub-tropics via the Kuroshio and East Australia Currents (Hu et al., 2015; Todd et al., 2019). During a La Niña event, the WPWP is anomalously warm and rainfall increases, and the opposite occurs in an El Niño event (Bjerknes, 1966; Wyrkti, 1974; McPhaden, 1999). During El Niño, longitudinal gradients of SST and sea surface salinity (SSS) anomalies form as the weaker trade winds deliver “less-warm” and saltier water to the WPWP (McPhaden and Picaut, 1990; Picaut et al., 1996; Delcroix and McPhaden, 2002; McPhaden, 2018). Recent studies have also shown differences in the spatial SST and SSS signatures of “central” versus “eastern” types of El Niño events (Singh et al., 2011; Capotondi et al., 2015; Qi et al., 2019). Changes in the WPWP are therefore reflective of the intensity and location of ENSO events and provide an ideal opportunity to study past ENSO variability (Wang and Liu, 2016; Hu et al., 2017; Kidwell et al., 2017). Unfortunately, the sparsity and short temporal length of climate records in this region have prevented us from understanding past warm pool zonal migrations at decadal to centennial timescales (Gravatte et al., 2009). Paleoclimate records from across this region would allow studying the extension of WPWP reconstructions and provide a more holistic understanding of WPWP and ENSO variability back through time.

Paleoclimate reconstructions from fast-growing, long-lived corals are valuable for extending the tropical instrumental record, including ENSO, beyond the onset of the industrial revolution in the late 1800s (Quinn et al., 1996; Alibert and Mc Culloch, 1997; Zinke et al., 2005; Mitsuguchi et al., 2008). The ratio of stable oxygen isotopes (δ18O/δ16O, reported as δ18O relative to a standard) in corals is commonly used as a combined proxy of SST and SSS (Epstein et al., 1953). During calcification, coral δ18O (δ18Oc) varies in response to both the temperature and seawater δ18O composition (δ18Osw) of the water surrounding the coral colony. Generally, δ18Osw has a linear relationship with SSS (Urey, 1947). Also, corals incorporate relatively less Sr into their calcium carbonate (CaCO3) skeleton with increasing temperatures, therefore resulting in an inverse correlation between Sr/Ca ratios and SST (Smith et al., 1979). Sr/Ca is insensitive to changes in SSS and is therefore commonly used to reconstruct SST (Beck et al., 1992; Alibert and Mc Culloch, 1997; Heiss et al., 1997; Gagan et al., 1998; Hughen et al., 1999; Corrêga et al., 2000; Linsley et al., 2000; Hendy et al., 2002; Fallon et al., 2003; Felis et al., 2004; Linsley et al., 2004; Stephens et al., 2004; Goodkin et al., 2005; Quinn et al., 2006; De Long et al., 2007; Pfeiffer et al., 2009; De Long et al., 2011; De Long et al., 2012; Wu et al., 2013; Bolton et al., 2014; Sagar et al., 2016; Ramos et al., 2017). Due to its fidelity as a proxy for SST, Sr/Ca is frequently used to remove the temperature signal from coral δ18O. Through coupled Sr/Ca and δ18O measurements, Sr/Ca-predicted SST is substracted from the δ18O signal to derive a record of residual sea water δ18O, or δ18Osw (Mc Culloch et al., 1994; Gagan et al., 1998; Ren et al., 2003; Cahyarini et al., 2008). The resulting δ18Osw record can then be used to reconstruct past changes in surface hydrology (precipitation-evaporation as well as advection) over the past decades to centuries (Corrêga et al., 2004; Linsley et al., 2004; Bolton et al., 2014; Hennekam et al., 2018; Pfeiffer et al., 2019).

The long-lived coral genus Porites spp. are common in the Indo-Pacific and known for preserving reliable paleoclimate information. Although some factors (e.g., changes in coral vital effects or Sr/Ca of sea water) have been identified as possible sources of non-temperature influences on the coral Sr/Ca paleothermometer (e.g., (de Villiers et al., 1995; Shen et al., 1996; de Villiers, 1999; Cohen et al., 2001; Cohen et al., 2002; Allison and Finch, 2004; Alibert and Kinsley, 2008; Grove et al., 2013; Alpert et al., 2016; Kuffner et al., 2017), many studies have shown success in accurately reconstructing SST from coral Sr/Ca (Mc Culloch et al., 1994; Marshall and Mc Culloch, 2001; Goodkin et al., 2005; De Long et al., 2007; Goodkin et al., 2007; Cahyarini et al., 2009; Pfeiffer et al., 2009; De Long et al., 2011; De Long et al., 2013; Wu et al., 2013; Bolton et al., 2014; Ramos et al., 2017; Pfeiffer et al., 2019). Also, a recent study investigating variability in Sr/Ca-SST calibrations across large SST gradients showed that the Sr/Ca-SST slopes do not change randomly but vary systematically with mean SST (Murtie et al., 2018). While Porites are typically fast-growing corals with minimal growth impacts, calibrating Sr/Ca from each colony against recent instrumental SST is still required to accurately reconstruct SST back in time. Similarly, δ18O may also experience different sensitivities to SST and SSS, given δ18Osw range of variability may be significant relative to SST (Tudhope et al., 2001; Linsley et al., 2004; Russon et al., 2013) in the context of resultant δ18O variability. Within the eastern and central tropical Pacific, δ18O tracks variations in ENSO driven mostly by changes to SST (Dunbar et al., 1994; Cobb et al., 2003; Nurhati et al., 2011), whereas central to western Pacific δ18O tracks ENSO through changes in SST and rainfall (Cole et al., 1993; Tudhope et al., 2001; Quinn et al., 2006; Carilli et al., 2014). Recent in-situ seawater δ18O-SSS studies suggest a trend of increasing sensitivities from the eastern to western Pacific, implying differences in the spatial seawater δ18O-SSS relationship (Conroy et al., 2014; Conroy et al., 2017). These findings are coherent with modelling studies, which show significant uncertainties in reconstructing δ18O values due to variable δ18Osw impacted by ENSO (Liu et al., 2014; Stevenson et al., 2015). Careful, site-specific calibrations of δ18O, to instrumental SST and SSS data are therefore also required for each colony.

Our study examines two corals from either side of the heart of the WPWP that capture the longitudinal seesaw of SST and SSS anomalies during ENSO events. We investigate calibrations between coral proxies (Sr/Ca and δ18O) and instrumental SST and SSS, at multiple timescales (monthly, interannual). Additionally, to quantify potential sensitivity of the WPWP to ENSO variability, coral-based zonal SST and SSS gradients
between the two sites are examined for correlations to instrumental ENSO indices. Such spatial information captured in these corals would provide valuable new constraints on not just intensity but type (“eastern” versus “central”) of ENSO events.

2. Materials and methods

2.1. Region of study

The islands of the Federated States of Micronesia (FSM) are spread near the equator within the WPWP, characterized by warm mean annual SSTs (> 28 °C) (Wyrtki, 1989) and heavy rainfall inducing SSS below 35 practical salinity units (psu) (Carton et al., 2016). Woleai Atoll (7° 21′ 59.99″ N, 143°53′ 59.99″ E, WOL) and Kosrae Island (5° 18′ 60.00″ N, 162° 58′ 59.99″ E, KOS) are located near the eastern edge of the WPWP (Fig. 1) and show independent seasonal variability dependent on the meridional movement of the warm pool (Yan et al., 1992).

Both sites capture seasonal SST variability, displaying maxima during wet season (July-September) (~29.5 °C) and dry season (January-April) (~28.5 °C) ((Reynolds et al., 2002); Fig. 1c, d).

The WPWP exhibits a salinity front (isohaline ~34.6 psu) between the warm-fresh waters of the North Equatorial Countercurrent and less warm-saltier waters of the South Equatorial Current (Fig. 1a, b) (Delcroix and Henin, 1991; Picaut et al., 1996; Hu et al., 2015). Salinity fronts are also observed at the boundaries of the Inter Tropical Convergence Zone (ITCZ), as seawater salinity increases with decreasing precipitation (Eldin et al., 2004; Kao and Lagerloef, 2015) (Fig. 1b; 34.5-35 salinity band). The salinity front is closest to Kosrae Island (~34.4 psu) and Woleai Atoll (~34.2 psu) during the dry season when both the warm pool and ITCZ migrate to their southernmost extent (Delcroix and Henin, 1991; Carton et al., 2016). During this period, both sites’ SSS maxima coincide with the mean precipitation and SST minima observed from a 30-year seasonal climatology (Fig. 1c, d).

At interannual timescales, the salinity front and the eastern edge of the WPWP are subject to zonal migrations of up to several thousands of kilometers, eastward and westward during mature phases of El Niño and La Niña, respectively (Picaut et al., 1996; Delcroix, 1998; Maes et al., 2004). The January to April (JFMA) SSS and SST anomalies for El Niño and La Niña events reveal that Woleai Atoll and Kosrae Island experience opposite changes reflective of the extent of zonal migration of the WPWP influenced by ENSO (Fig. 2). These opposite relationships provide a distinct spatial signature of ENSO variability that can be distinguished from background trends (e.g., regional or global warming), and record changes due to the type (“eastern” versus “central”) as well as the intensity of ENSO events.

2.2. Coral collection, sampling, and analysis

Porites spp. coral cores from two separate regions of the FSM were drilled during the R/V Alucia Micronesia expedition in October 2012. Both coral cores were taken along the colony growth axis using an underwater hydraulic drill. The first coral core, measuring 4.6 m long, was sampled adjacent to the southern islet of WOL (7.4°N, 144°E) close to one of several entrances where open ocean waters flush the lagoon. The second coral core, measuring 3.5 m long, was retrieved off the southern coast of KOS (5.3°N, 163°E) and was directly exposed to open-
ocean waters. Unlike WOL, KOS may experience land-sea thermal gradients due to larger landmass compared to smaller islets of WOL.

Five-millimeter slabs were cut from the cores with a diamond-blade rock saw at Woods Hole Oceanographic Institution (WHOI). Each slab was soaked in bleach, rinsed and subsequently ultrasonicated in deionized water for 15 min and dried for 48 h in a 50 °C oven. Slabs were then x-rayed at the Diagnostic Imaging Laboratory at the National University Hospital Singapore at 50 kV, 10 mA, 500 ms, and a focal point of 100 cm. The x-ray positives allow for the visualizing of annual density bands and delineating sampling paths parallel to the extending corallites (Fig. 3, Fig. S2). Infrequent skeletal anomalies can be seen in the x-rays and slab surfaces, and sampling tracks are selected to avoid any such anomalies. In addition, skeletal density was determined along the sampling track based on calibrated optical density in the x-rayographs (Carricart-Ganivet and Barnes, 2007). We found no systematic changes in mean skeletal density along the sample track, indicating no addition of secondary aragonite (Hendy et al., 2007) (Fig. S1).

The top 47 cm of KOS and 30 cm of WOL coral slabs were sampled at 0.5 mm intervals using a manual drill press fitted with a one mm drill bit. The sampling path was consistently drilled to one mm depth, generating approximately 250–350 μg of coral powder. The powder samples were split to allocate 50–80 μg for stable oxygen isotope analysis and the remainder for trace element analysis.

Stable isotope analysis was conducted on a Thermo Fisher MAT-253 Isotope Ratio Mass Spectrometer (IRMS) coupled to a Kiel IV Kiel Carbonate Device at the Asian School of the Environment (ASE) to generate the WOL and KOS δ18O records. Isotopic measurements were calibrated relative to Vienna Peedee belemnite (VPDB) using Natural Bureau of Standards (NBS)-19 (−2.20‰) (Stichler, 1995) with further linear calibration to a range of standards with NBS-18 at a minimum (δ18OVPDB = −23‰). Carbonate standards (Carrara, TSF and Estremoz) were repeatedly measured yielding average values of −1.964‰ (∆ 0.06‰, N = 2195), −2.254‰ (∆ 0.07‰, N = 1649) and −5.972 (± 0.07‰, N = 2006), respectively.

Sr/Ca of WOL slabs were analyzed at ASE, and Sr/Ca of KOS was analyzed at WHOI; both on Thermo I-Cap Inductively Coupled Optical Emission Spectrometers (ICP-OES). Powder samples were digested with 2.5 ml of 5% HNO3 in an 8 ml tube, vortexed for 30 s and left to homogenize overnight. A reference solution was measured between every sample to correct for instrumental drift, and calibration standards were routinely analyzed to correct for matrix effects as a result of variable calcium concentration (Schrag, 1999). Analytical precision and accuracy were monitored by measuring reference standard JCp-1 (Okai et al., 2002) and an in-house standard Bunaken. The reproducibility of JCp-1 at ASE is 0.18% (average 8.824 ± 0.018 mmol/mol, n = 1146) and at WHOI is 0.10% (average 8.828 ± 0.009 mmol/mol, n = 124), consistent with interlaboratory values (8.838 ± 0.089 mmol/mol) (Hathorne et al., 2013). Bunaken standards measured at WHOI were also within uncertainties of ASE (8.838 ± 0.014 mmol/mol, n = 971, 8.819 ± 0.023 mmol/mol, n = 432; average and number of observations at WHOI and ASE respectively).

2.3. Climate data sources to build coral age model

Gridded instrumental and reanalysis products were utilized to build coral age model. For SSS, monthly resolved gridded 0.25° × 0.25° Simple Ocean Data Assimilation / Sea Ice Reanalysis v3 (SODA) (Carton et al., 2016) data centered at 7.25°N, 143.75°E (Woleai Atoll) and
5.25°N, 162.75°E (Kosrae Island) were used. For SST, gridded 1° × 1° monthly NOAA Optimum Interpolation SST v2 data (OISST) (Reynolds et al., 2002) centered at 7.5°N, 143.5°E (Woleai Atoll) and 5.5°N, 162.5°E (Kosrae Island) were utilized.

5.2. Establishing coral chronologies

The annual chronology of KOS was established by counting annual density bands in coral x-ray images (Fig. 3b), where a light and a dark pair of bands indicate one year. However, this method could not be applied to WOL due to less well-defined banding (Fig. 3a), which may have resulted from sub-optimal corallite orientation due to variable growth directions, microenvironment, or species-specific factors (Knuston et al., 1972; DeLong et al., 2013). To further refine the age models of our corals, we developed pseudo-coral δ18O records (δ18Opseudo) for the KOS and WOL sites calculated by the known thermodynamic relationships of δ18O to SST and SSS. First, to calculate seawater δ18O (δ18Osw), we applied site-centered monthly gridded SODA SSS (1986–2012) to the regionally established δ18Osw-SSS relationship based on an in-situ study from the Western Pacific (Morimoto et al., 2002) (Eq. (1)). Site-centered gridded δ18Osw and SST data (1986–2012) were then incorporated into the δ18O-SST paleothermometer calibration equation derived from (Leclerc and Schmidt, 2001) to generate δ18OpseudoKOS and δ18OpseudoWOL, representing thermodynamic carbonate values (Thompson et al., 2011) (Eq. (2)). We adopted the intercepts from the original studies as the pseudocoral is only used to assign annual tie points, not convert data.

\[
\delta^{18}O_{\text{sw}} = 0.4236 \times \text{SSS}_{\text{SODA}} - 14.244 \\
\delta^{18}O_{\text{pseudo}} = 0.45 - 0.2 \times \text{SST}_{\text{OISST}} + \delta^{18}O_{\text{sw}}
\]

We performed a 3-step procedure to peak-match coral proxies to gridded climate variables. The first step was to age-assign annual tie points between δ18Opseudo and δ18Oc using Analyseries software (Paillard et al., 1996). Enriched (depleted) δ18Opseudo was aligned with seasonally enriched (depleted) δ18Oc (Fig. S1). An additional two tie-points were prescribed sub-annually at inflection points between seasonal warm/wet and cool/dry extremes. Second, these tie-points were applied to the corresponding Sr/Ca record and fine-tuned against site-centered SSTOISST data to ensure that Sr/Ca maxima align with SST minima and yield strong correlations. Next, the fine-tuned tie-points were re-applied to the δ18O record for comparison to δ18Opseudo to ensure peaks and troughs still match, and optimize the relationships between both proxies (δ18OpseudoKOS, Sr/Ca) and gridded variables (δ18OpseudoWOL, SST). Finally, the age-modelled proxy records (δ18OpseudoKOS, Sr/Ca) were linearly interpolated to generate records at monthly timescales.

3. Results

3.1. Monthly reconstruction and calibration of SST

Both sites have a similar mean seasonal Sr/Ca range of 0.068 mmol/mol (8.653 to 8.722 mmol/mol) at WOL and 0.073 mmol/mol (8.757 to 8.830 mmol/mol) at KOS. Type (II) Pearson’s Major axis linear regressions of monthly Sr/Ca to WOL and KOS SST reveal significant inverse relationship (Fig. 4a):

\[
\text{WOL Sr/Ca} = 10.188 \pm 0.018 - 0.052 \pm 0.003 \times \text{SST} \quad (°C)
\]

\[
\text{KOS Sr/Ca} = 10.861 \pm 0.029 - 0.071 \pm 0.005 \times \text{SST} \quad (°C)
\]

\[
r = -0.65, \ p < 0.0001, \ RMSR = 0.6 \ °C, \ n = 324, \ SST \ range = 2.8 \ °C, \ years 1986-2012.
\]

\[
r = -0.60, \ p < 0.0001, \ RMSR = 0.6 \ °C, \ n = 300, \ SST \ range = 2.5 \ °C, \ years 1988-2012
\]

where root mean squared of the residual (RMSR) measures the average absolute residuals between the instrumental and reconstructed SST.

While both coral sites have relatively similar SST ranges, and monthly Sr/Ca-SST slopes are in agreement with previous studies (Alibert and McCulloch, 1997; Gagan et al., 1998; Marshall and McCulloch, 2002; Quinn and Sampson, 2002; Linsley et al., 2004; Quinn et al., 2006; Wu et al., 2013; Sadler et al., 2016; Brenner et al., 2017), WOL has a shallower slope (−0.052 mmol/mol°C−1) compared to KOS (−0.071 mmol/mol°C−1). Coral sub-sampling resolution is high, due to a KOS extension rate of 18.5 mm year−1 and WOL of 11 mm year−1, providing 37 and 22 samples per year, enough to resolve ~bi-weekly SST changes. Coral extension rates differ between species, and could potentially account for slope differences through ‘bio-smoothing’ or the infilling of the skeleton with aragonite precipitated in
Fig. 4. Sr/Ca (mmol/mol) from KOS (orange) and WOL (green) are inversely and significantly correlated with OISST at a) monthly, b) seasonal dry (JFMA), c) wet (JJAS) and d) annual timescales. Reconstructed coral SST at e, f) monthly, g, h) dry, i, j) wet, and k, l) annual shown temporally and compared to OISST. Seasonal dry, wet and annual RMSR of KOS$_{\text{dry}}$ = 0.50 °C, 0.60 °C, 0.50 °C and WOL$_{\text{dry}}$ = 0.60 °C, 0.60 °C, 0.50 °C shown in gray shadings, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
the subsequent season, with different SST and Sr/Ca values and thus attenuation of the geochemical signals (Gagan et al., 2012). To estimate the duration of bio-smoothing within our sites, we divide the mean tissue layer thickness (6 mm year⁻¹ for both corals) (i.e., Lough and Barnes, 1997, 2000) over the mean linear extension rate. We found a greater influence of smoothing on WOL than on KOS, ~6.5 versus 4.5 months, respectively. The longer period in smoothing for WOL potentially results in a dampered seasonal Sr/Ca-ST slope.

Similar to past coral calibration studies (de Villiers et al., 1995; Linsley et al., 2006; Pfeiffer et al., 2009), our monthly regression equations for both KOS and WOL show independent coefficients, which may be caused by site-specific mean Sr/Ca offsets. KOS exhibits a greater mean Sr/Ca value (8.80 mmol/mol) than WOL (8.69 mmol/mol). We found that the mean values are consistent within a coral record even when averaged at shorter 10-year periods (1988–1998, 1998–2008), suggesting that the record length has minimal influence on mean Sr/Ca and that there is no measurable influence of diagenesis (Müller et al., 2001; Hendy et al., 2007; Sayani et al., 2011). Analytical precision is not the source of the Sr/Ca offset, which is seven times greater than our analytical error. Inter-laboratory comparisons between ASE and WHOI using both JCP-1 and Bunaken standards yield results within 1σ (see Methods), and therefore laboratory differences are not contributing to creating the offset. Both KOS and WOL are fast-growing corals and mean annual Sr/Ca does not correlate to linear extension rate (p = 0.55 and 0.44 for WOL and KOS, respectively). The insig-
nificant relationship of Sr/Ca to linear extension suggests that observed offsets are not the result of growth-related effects, implying that other non-environmental effects may influence the offsets (Mitsuguchi et al., 2003; Allison and Finch, 2004). Nevertheless, the strong relationship between monthly Sr/Ca and instrumental SST, and calibration un-

certainties less than 25% of the mean SST range (Table 1), indicates that monthly SST variability is reproducible.

3.2. Inter-annual Sr/Ca-ST calibration

As monthly correlations are largely driven by the amplitude of the seasonal cycle (Crowley et al., 1999; Goodkin et al., 2005; Pfeiffer et al., 2009), we test the strength of the Sr/Ca-ST relationships by investigating interannual timescales. To derive Sr/Ca-ST calibrations based on interannual variability, 4-month wet season (JJAS), 4-month dry season (JFMA), and mean annual averages were determined based on precipitation climatologies (Fig. 1). Despite a ten-fold decrease in the number of observations from monthly to interannual timescales (dry season, wet season and mean annual), all of the Sr/Ca versus OISSERT interannual regressions indicate significant relationships (p < 0.05) (Fig. 4 b, c & d). The reconstructed interannual STTs also display ENSO-influenced 4–6 year cycles, as observed in instrumental ENSO indices as well as coral-based interannual ENSO reconstructions (Cobb et al., 2003; Juillet-Leclerc et al., 2006; Quinn et al., 2006) (Fig. S3). The significant Sr/Ca-ST calibrations for KOS and WOL indicate that Sr/Ca is a robust paleothermometer, capturing interannual SST variability over multiple timescales (r = −0.64 to −0.70, p < 0.0001 WOL; r = −0.41 to −0.55, p < 0.05 KOS; Table 1).

To evaluate the interannual calibration equations further, we compared the differences between Sr/Ca-ST slopes at different timescales. The interannual Sr/Ca-ST slopes for KOS and WOL displayed different sensitivities but are within the expected range of past mean annual Sr/Ca-ST calibration studies (~0.05 to −0.10 mmol/mol/1°C). Both KOS and WOL mean annual Sr/Ca-ST slopes increased in sensitivity to −0.080 mmol/mol°C⁻¹ and −0.074 mmol/mol°C⁻¹, respectively. Dry season calibration slopes remained consistent with monthly calibration slopes, whereas the wet season slopes for both sites increased relative to monthly (Table 1). The wet season Sr/Ca-ST regression slopes may be steepened due to the narrow range of gridded SST (wet season OISSERT range = 1°C) relative to local SST changes experienced at the study sites, which are in shallower water with a likely larger SST range.

Similarly, we examined the correlation and calibration errors across different timescales. Although all of the interannual calibration relationships are significant, the interannual WOL Sr/Ca-ST correlations mostly became stronger (monthly r = −0.65, p < 0.05; dry, wet and mean annual r = −0.70, −0.64, −0.70, p < 0.0005), whereas KOS Sr/Ca-ST correlations weakened (monthly r = −0.60, p < 0.05; dry, wet and mean annual r = −0.42, −0.55, −0.41, p < 0.05) (Table 1). The interannual calibration uncertainties (RMSR) of KOS increased by 10–49% relative to monthly timescales (Table 1). The weakened in-
erannual Sr/Ca-ST relationship at KOS may be related to a number of potential causes: 1) the large gridded 1° × 1° OISSERT dataset may mis-
represent local KOS SST changes; 2) the ‘landmass effect’ may influence local SST at KOS, where the coral is close to Kosrae Island, compared to Woleai Atoll which better represents open oceanographic conditions (Palacios, 2002; Elliott et al., 2012).

3.3. WPWP SST variability due to ENSO

To investigate changes in WPWP SST due to ENSO variability, we compared interannual SST reconstructions from WOL and KOS to the Niño 4 index. The Niño 4 index is calculated from SST anomalies over the central tropical Pacific within the 5°S–5°N, 160°E–150°W region (Trenberth and Stepaniak, 2001). El Niño (La Niña) events are defined by Niño4 SST anomalies above 0.4°C (below −0.4°C) over a 6-month period. To allow comparison of dry season coral reconstructed SST re-
cords during the Northern winter, a season when ENSO amplitude frequently peaks (Rasmussen and Carpenter, 1982; Trenberth, 1997), we averaged the JFMA months of Niño4 anomalies (Niño4dry). Also, the coral SST records were normalized to calculate dry season anomalies by subtracting mean SST from each record and dividing by its standard deviation (WOldry, KOSdry). KOSdry showed a positive correlation to Niño4dry (r = 0.54, p < 0.05, n = 25; Fig. 5a, e), whereas Wolidry, in contrast, displayed a negative correlation to Niño4dry (r = −0.50, p < 0.05, n = 27; Fig. 5b, f). As predicted by the WPWP spatial SST composite maps (Fig. 2a, b), WOL records cool anomalies during El Niño events whereas KOS experiences warm anomalies. The reverse occurs during La Niña events at both sites.

To capture the spatial WPWP SST variability driven by ENSO, we subtracted the normalized SST anomalies of WOLIDRy, from KOSdry, to calculate a KOSWOLDry index. Correspondingly, we also derived KOSWOLSInstrumental index using gridded OISST from each site. The coral derived KOSWOLSInstrumental index shows a strong correlation to Niño4 (r = 0.63, p < 0.05, n = 25; Fig. 5c, g), greater than either site alone. The ability of the coral KOSWOLSInstrumental index to capture spatial WPWP SST variability is confirmed by its very strong correlation to KOSWOLSInstrumental (r = 0.77, p < 0.05, n = 25; Fig. 5d, h). These robust temporal and spatial SST relationships driven by ENSO (Fig. 5g, h) suggest an eastward expansion (contraction) of the WPWP during El Niño (La Niña) events.

3.4. Monthly seawater (δ¹⁸Osw) reconstruction and calibration

Like Sr/Ca, the seasonal δ¹⁸Osw ranges of 0.210% and 0.214% are similar for both sites, with values between −5.489 to −5.699% at KOS and −5.458 to −5.672% at WOL. Comparing the δ¹⁸Osw records to the calculated instrumental pseudocoral time series validates the joint influence of SST and SSS on δ¹⁸Osw for both KOS and WOL. (Supplementary Information). To remove the thermal effect from δ¹⁸Osw, and isolate the δ¹⁸Osw reflective of SSS, we followed the centering approach outlined by Cahyarinii et al. (2008):

δ¹⁸Osw = (δ¹⁸Osw − δ¹⁸Osw) − (Sr/Ca−Sr/Ca)

where δ¹⁸Osw is determined by removing the monthly Sr/Ca anomalies from δ¹⁸Osw anomalies, γ is each site’s δ¹⁸Osw–ST (Sr/Ca) slope (~0.082 and −0.116% °C⁻¹ for WOL and KOS, respectively) and β is the Sr/
Recent in-situ studies across the tropical Pacific establish variable \( \delta^{18}O_{sw}-SSS \) slopes, which show an increasing trend from the eastern to western Pacific (Conroy et al., 2017). Both WOL and KOS monthly \( \delta^{18}O_{sw}-SSS \) slopes fall within previously reported slopes for the Western Pacific sites of Palau and Papua New Guinea (Morimoto et al., 2002; Conroy et al., 2014). While both corals have similar \( \delta^{18}O_{sw} \) ranges, WOL located further west has a steeper slope (0.299‰ psu \(^{-1}\)) compared to KOS (0.261‰ psu \(^{-1}\)). The steeper slope for WOL is despite the higher salinity range, which results largely from higher observed precipitation changes compared to KOS (Fig. 1). To evaluate the robustness of the \( \delta^{18}O_{sw}-SSS \) calibration, interannual calibrations were investigated (dry season, wet season, and mean annual).

### 3.5. Reconstructing interannual \( \delta^{18}O_{sw}(SSS) \) at respective sites

Monthly \( \delta^{18}O_{sw} \) was averaged for dry season (JFMA), wet (JJAS), and mean annual timescales to create interannual time series. Despite a 90% decrease in observations, interannual \( \delta^{18}O_{sw}-SSS \) regressions remained significant (\( p < 0.05 \)) (Fig. 6b, c, and d). The interannual \( \delta^{18}O_{sw}-SSS \) relationships also remained consistent with minimal changes in correlation strength relative to monthly relationships (Table 1).

### Table 1
Pearson least square linear regression of Sr/Ca versus OISST and \( \delta^{18}O_{sw} \) versus SODA SSS for KOS and WOL at monthly, seasonal dry (JFMA), wet (JJAS) and annual timescales.

| Proxy = m \( \times \) SST + b | m 1σ error (m) | b (y-intercept) 1σ error (b) | r | p  | RMSR (°C) | Gridded SST range | Percentage error relative to SST range (%) | n |
|---|---|---|---|---|---|---|---|---|
| Monthly proxy data Sr/Ca (mmol/mol) | | | | | | | | |
| KOS | −0.07 | 0.01 | 10.86 | 0.03 | −0.60 | < 0.01 | 0.6 | 2.5 | 24 | 300 |
| WOL | −0.05 | 0.01 | 10.19 | 0.02 | −0.65 | < 0.01 | 0.6 | 2.8 | 21 | 324 |
| Dry (JFMA) | | | | | | | | | |
| KOS | −0.05 | 0.02 | 10.24 | 0.10 | −0.42 | 0.04 | 0.5 | 1.5 | 34 | 25 |
| WOL | −0.07 | 0.01 | 10.61 | 0.07 | −0.70 | < 0.01 | 0.6 | 1.7 | 34 | 27 |
| Wet (JJAS) | | | | | | | | | |
| KOS | −0.10 | 0.03 | 11.80 | 0.17 | −0.55 | 0.004 | 0.6 | 1.0 | 56 | 25 |
| WOL | −0.06 | 0.01 | 10.56 | 0.08 | −0.64 | < 0.01 | 0.6 | 1.0 | 62 | 27 |
| Annual | | | | | | | | | |
| KOS | −0.08 | 0.04 | 11.14 | 0.19 | 0.41 | 0.04 | 0.5 | 0.6 | 73 | 25 |
| WOL | −0.07 | 0.01 | 10.85 | 0.08 | 0.70 | < 0.01 | 0.5 | 1.0 | 51 | 27 |
| Monthly proxy data \( \delta^{18}O_{sw} \) | | | | | | | | | |
| KOS | 0.29 | 0.03 | −8.95 | 0.15 | 0.50 | < 0.01 | 0.3 | 1.6 | 17 | 300 |
| WOL | 0.30 | 0.03 | −10.17 | 0.18 | 0.47 | < 0.01 | 0.4 | 1.4 | 28 | 324 |
| Dry (JFMA) | | | | | | | | | |
| KOS | 0.29 | 0.12 | −9.89 | 0.71 | 0.43 | 0.04 | 0.4 | 0.8 | 49 | 25 |
| WOL | 0.47 | 0.15 | −16.15 | 0.15 | 0.53 | < 0.01 | 0.3 | 0.5 | 53 | 27 |
| Wet (JJAS) | | | | | | | | | |
| KOS | 0.28 | 0.11 | −9.52 | 0.62 | 0.46 | 0.02 | 0.4 | 0.9 | 45 | 25 |
| WOL | 0.23 | 0.07 | −7.99 | 0.40 | 0.55 | < 0.01 | 0.3 | 1.1 | 25 | 27 |
| Annual | | | | | | | | | |
| KOS | 0.36 | 0.11 | −12.31 | 0.67 | 0.53 | < 0.01 | 0.4 | 0.8 | 47 | 25 |
| WOL | 0.31 | 0.07 | −10.58 | 0.42 | 0.64 | < 0.01 | 0.2 | 0.8 | 23 | 27 |
The changes in slopes may be related to the decreasing variance of the gridded SSS, which artificially steepens the $\delta^{18}O_{\text{sw}}$-SSS slopes. However, the insignificant correlation versus variance ($r = -0.67, p > 0.05, n = 8$) suggests that more observations are required to test both relationships.

### 3.6. WPWP SSS variability due to ENSO

To investigate the impact of ENSO on spatial and temporal variability in WPWP precipitation, KOS and WOL dry season SSS were compared to the El Niño Southern Oscillation Precipitation Index (Fig. 5).
Fig. 6. $\delta^{18}O_{sw}$ (%) from KOS (orange) and WOL (green) are significantly correlated to SODA SSS at a) monthly, b) seasonal dry (JFMA), c) wet (JJAS) and d) annual timescales. Reconstructed coral SSS (PSU) at e, f) monthly, g, h) dry, i, j) wet, and k, l) annual shown temporally and compared to SODA SSS. Seasonal dry, wet and annual RMSR for KOS$_{RMSR}$ = 0.40 psu, 0.35 psu, 0.35 psu and WOL$_{RMSR}$ = 0.30 psu, 0.30 psu, 0.20 psu shown in gray shadings, respectively.
ESPI tracks precipitation gradients between the Maritime Continent and the Equatorial Pacific region (Curtis and Adler, 2000). Positive (negative) ESPI values indicate El Niño (La Niña) phase of the ENSO cycle. Using an approach similar to comparing SST reconstructions and the Niño4 index during frequent ENSO peak amplitude, we normalized the dry season SSS reconstructions by removing the temporal mean and dividing the anomalies by the standard deviation (KOS\textsubscript{dry} and WOL\textsubscript{dry}). Similarly, we averaged the dry season months (JFMA) of ESPI to produce ESPI\textsubscript{dry}. We observe positive correlations of both KOS\textsubscript{dry} and WOL\textsubscript{dry} to ESPI\textsubscript{dry} (r = 0.40, p < 0.05, n = 25, and r = 0.48, p < 0.05, n = 27, respectively) (Fig. 7a, b, e, f). These relationships indicate that dry season SSS records at KOS and WOL both capture anomalous precipitation changes driven by ENSO.

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evaluated whether KOS and WOL together can capture additional WPWP regional SSS variability by averaging the normalized SSS anomalies of KOSSS and WOLSS to generate a KOSWOLSST index (Fig. 7c). Comparably, we also derived KOSWOLInstrumental SSS using gridded SODA SST of each site. The KOSWOLSST index shows a stronger correlation to ESPI ($r = 0.53, p < 0.05, n = 25$) than either coral site individually, demonstrating the value of multiple locations to capture spatial as well as temporal variability (Fig. 7c, g). The KOSWOLSST index also showed comparable relationships to KOSWOLInstrumental SSS ($r = 0.59, p < 0.05, n = 25$, Fig. 7d, h), reinforcing the importance of the coral index for capturing gridded SSS variability. Lastly, both KOSWOLSST index and KOSWOLInstrumental SSS showed significant relationships to Niño 1,2 ($r = 0.53, p < 0.05, n = 25$, and $r = 0.61, p < 0.05, n = 25$, respectively) (Fig. S6). These relationships imply ENSO driven Eastern Pacific SST anomalies may be phased locked to the WPWP hydrological changes.

4. Discussion

Our major findings are two-fold. First, coral proxies Sr/Ca and δ18Osw from both KOS and WOL sites are capable of accurately reconstructing climate variables SST and SSS at monthly and interannual (dry season, wet season, and mean annual) timescales, including the directions of change driven by ENSO events. Second, combining individual climate records from each site to generate spatial indices (KOSWOLSST and KOSWOLSST) captures the distinct spatial SST and SSS signatures within the WPWP caused by ENSO. For Sr/Ca, the multi-timescale calibrations to instrumental SST are all significant at both sites ($p < 0.05$). The difference between reconstructed dry season SST anomalies from both sites (KOSWOLSST index) is highly sensitive to the spatial migration of the WPWP influenced by ENSO and provides a valuable tool for reconstructing past ENSO behavior. Similarly, calibrations of δ18Osw to instrumental SSS at both sites are significant ($p < 0.05$) and have steep slopes reflective of high precipitation variability in the WPWP. The averaging of reconstructed dry season SSS anomalies from both sites (KOSWOLSST index) also captures the spatial signature of SSS change in the WPWP, recording the pattern of precipitation extremes driven by ENSO, and providing another strong proxy for reconstructing spatial as well as temporal ENSO variability in the past. The strong relationships of coral-based spatial indices to gridded instrumental spatial indices further supports the corals’ utility in tracking ENSO-driven changes. Future reconstructions of these spatial indices back through time will reveal detailed WPWP climate variability and changes in ENSO behavior in this important region over the past several centuries.

We observed no evidence of analytical or growth-related impacts influencing the mean Sr/Ca offset of 0.11 mmol/mol between KOS and WOL, despite similar ranges in SST. This difference is comparable to observed mean Sr/Ca offsets reported within colonies (DeLong et al., 2007), between colonies (Pfeiffer et al., 2009; Wu et al., 2014; Alpert et al., 2016; Sayani et al., 2019) and between sites (Linsley et al., 2006; Wu et al., 2013). Many studies suggest non-environmental ‘vital effects’ can influence the coral Sr/Ca-St-SST relationship and create offsets between nearby coral records (Gaetani and Cohen, 2006; Gagnon et al., 2007). We also observed weakened interannual Sr/Ca-St-SST correlations relative to monthly for KOS, which may be due to the greatly reduced range of SST variability, the influence of terrestrial area within a large 1° × 1° SST grid, or the impact of ‘landmass’ effects from Kosrae Island (Palacios, 2002; Elliott et al., 2012). Our multi-site study leaves room to speculate about spatiotemporal changes in seawater Sr/Ca ratios impacting mean Sr/Ca in corals (Shen et al., 1996; Sun et al., 2005). However, measurements of Sr/Ca in seawater within the WPWP are sparse, non-continuous, and distant from our study sites (de Villiers, 1999). Some studies recommend coral core replication to enhance climatic signals (Lough, 2004; DeLong et al., 2007; DeLong et al., 2011; Dassié et al., 2014), and we also recommend on-site monitoring of Sr/ Ca in seawater to identify potential source variability related to coral Sr/Ca and prevent erroneous interpretations of paleorecords (Linsley et al., 2006; Quinn et al., 2006).

We also demonstrated that it is possible to remove the thermal component from δ18O to derive regional hydrological records at these sites. Our corals’ δ18Osw-SSS sensitivities of 0.26 and 0.3%o °C−1 for KOS and WOL, respectively, are consistent with steep slopes expected from the WPWP based on regional calibration studies (Le Bec et al., 2000; Kilbourne et al., 2004), in-situ seawater studies (Morimoto et al., 2002; Conroy et al., 2017) and simulated δ18Osw-SSS in the WPWP (LeGrande and Schmidt, 2006). Depending on location, some calibration studies reported minimal or insignificant SST or SSS contributions to coral δ18O and attributed δ18O directly to a single variable (Le Bec et al., 2000; Wu and Grottioli, 2010; Dassié et al., 2014; Murty et al., 2017). Some studies removed the thermal component using instrumental SST (Iijima et al., 2005), while others found insignificant relationships between δ18Osw and gridded or in-situ SSS datasets (Quinn et al., 2006; Carilli et al., 2014). A lack of coral-derived δ18Osw-SSS relationship in other locations has been explained by 1) overly coarse sampling from limited ship tracks to resolve local SSS changes (Quinn et al., 2006; Maes et al., 2013; Boutin et al., 2016); 2) thermal stress to the coral impacting the Sr/Ca-St-SST relationship used to remove SST from δ18O (Marshall and Mc Culloch, 2002; Mitsuguchi et al., 2008; Sagar et al., 2016; Leupold et al., 2019); 3) low SST variability confounding the Sr/Ca signal for SST (Murty et al., 2018), compounded with analytical uncertainties (δ18O, Sr/Ca) masking δ18Osw variability (Cahynarini et al., 2008); and 4) covariance between SST and SSS leading to changes in δ18O-SST (Osborne et al., 2014). Based on these potential influences, it is significant that coral δ18Osw showed significant relationships to gridded instrumental SSS and a regional precipitation index at both of our sites, despite being within a region of minimal SST variability. The strong δ18Osw-SSS correlations seen here may be due to the high salinity variance within the region (Russan et al., 2013), resulting in a higher contribution of δ18Osw, compared to SST, to the total δ18O. Multiple linear regression of δ18O to instrumental SST and SSS provides evidence of a stronger SSS contribution than SST at both sites (Table S1). Nevertheless, the use of both SST and SSS in deriving the δ18Opseudo for age-modelling may have improved our δ18Osw calibrations, as well as separation of SST and SSS variables to quantify the hydrological contribution. During data analysis, we evaluated several methods for age-modelling the coral proxies and realized that some methods (e.g., directly pairing only Sr/Ca to SST, δ18O to SST, or δ18O to SSS) biased the latter proxy-climate relationships. Thus, for sites with strong SSS variability, we recommend age-modelling proxy δ18O to δ18Opseudo and then ‘fine-tuning’ Sr/Ca to SST to optimize reconstruction of both SST and SSS variables, as discussed in greater detail in the methods section.

Our multi-site coral indices track the zonal SST and SSS gradients within the WPWP, a key region regulating global climate teleconnections. The KOS and WOL sites, located near the heart of the warm pool itself, record hydrological changes due to zonal (east-west) migration of the WPWP during ENSO events. The strong correlations of the KOSWOInstrumental SST and KOSWOInstrumental SSS indices to the Niño 4 SST and ESPI SSS indices, respectively, show that we can derive past ENSO-driven spatial patterns with these corals. Consistent with Asami et al. (2004), our records show that not every reconstructed SST and SSS anomaly in the WPWP corresponds to a traditionally recognized ENSO event. Inferring from KOSWOInstrumental SST, the weak El Niño event in 1992 appears as a large positive anomaly in the WPWP, implying drier conditions in the WPWP comparable to the ‘larger’ 1997–1998 El Niño event. A positive anomaly in the instrumental KOSWOInstrumental index (Fig. 7h) at the same time verifies the anomaly and signals the eastern expansion of the WPWP. This supports the interpretation that distinct ENSO variability occurring within the WPWP region may not be equally expressed in the central Pacific.
5. Conclusions

In this ~30-year coral calibration study, we investigated coral cores from two separate sites in the Federated States of Micronesia to evaluate whether an individual and multi-coral reconstructions capture regional climate behavior across the WPWP. Each coral is found to individually capture changes in SST (via Sr/Ca) and SSS (via conversion of δ18Oc to δ18Osw) at monthly to interannual timescales. Subsequently, these reconstructions of SST and SSS at each site reliably reconstruct ENSO as recorded in regional instrumental indices. More importantly, the difference between each site's dry season SST anomalies (KOSWOLST index) tracks the spatial migration of the WPWP, and the average of SSS anomalies from both sites (KOSWOLSSS index) records the spatial SSS footprint, both due to ENSO variability. These climate gradients (KOSWOLST index and KOSWOLSSS index) provide powerful tools for investigating past climate behavior in the WPWP, and ENSO expression in the western Pacific, over the past several centuries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank two anonymous reviewers for their helpful comments that improved the manuscript. We also thank the crew of the M/V Alucia for assistance during the 2012 coral drilling expedition to FSM, funded by the Dalio Family Foundation through a WHOI Access to The sea grant to KAH (#25110104). Geochronological analysis was funded by Singapore Ministry of Education Academic Research Fund Tier-2 (#MOE2016-T2-1016) to NFG and KAH, and by the WHOI Summer Student Fellowship Program (00450400) and Coastal Preservation Network 501c to IMS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2020.110037.

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