



Research Article

Seasonal palaeoenvironmental variability during pre-industrial times revealed by a Southern Hemisphere *Tridacna* shell

Bohao Dong^{a,b}, Amy L. Prendergast^{a,b,*}, Sean Ulm^c, Kotaro Shirai^d, Russell N. Drysdale^a, Ian J. McNiven^e, Vladimir Levchenko^{f,c}, Henri Wong^f, Mark G. Meekan^{g,h}, Nguurruumungu Indigenous Corporationⁱ, Walmbaar Aboriginal Corporation RNTBC^j

^a School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Melbourne, Australia

^b ARC Centre of Excellence for Indigenous and Environmental Histories and Futures, The University of Melbourne, Melbourne, Australia

^c ARC Centre of Excellence for Indigenous and Environmental Histories and Futures, James Cook University, Cairns, Australia

^d Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba, Japan

^e ARC Centre of Excellence for Indigenous and Environmental Histories and Futures, Monash Indigenous Studies Centre, Monash University, Clayton, Australia

^f Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia

^g Oceans Institute, The University of Western Australia, Perth, Australia

^h Sharjah Marine Sciences Research Centre, University of Khorfakkan, Khorfakkan 18119, Sharjah, United Arab Emirates

ⁱ PO Box 886, Cooktown, Queensland, Australia

^j 24 Flierl Street, Hope Vale, Queensland, Australia

ARTICLE INFO

Editor: Dr. Fabienne Marret-Davies

Keywords:

Giant clam
Quaternary
Holocene
Past climate
Sclerochronology
Isotope
ENSO

ABSTRACT

The end of the Little Ice Age (LIA) represents a key pre-industrial climate interval, marking the final major cooling phase before widespread anthropogenic warming after the mid-nineteenth century. However, high-resolution evidence for this transition remains dominated by Northern Hemisphere archives, limiting understanding of how low-latitude marine environments in the Southern Hemisphere responded to late-LIA climate variability. Here, we analysed a *Tridacna gigas* shell that lived for approximately 30 years during the early 1800s to provide a high-resolution 30-year snapshot of environmental variability at Jiigurru (Lizard Island Group) in the northern Great Barrier Reef (GBR), tropical Southern Hemisphere. Stable isotope records ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) from both the inner and outer shell layers were applied to reconstruct SST, precipitation variability, and local ENSO-like events. Our results suggest that cooling associated with the LIA extended to the northern GBR. Under a constant modern SSS-derived $\delta^{18}\text{O}_{\text{Seawater}}$ baseline, reconstructed SSTs were $\sim 0.9\text{--}1.2\text{ }^{\circ}\text{C}$ lower than modern instrumental records, a monthly SSS-corrected sensitivity reconstruction reduced this estimate to $\sim 0.6\text{--}0.9\text{ }^{\circ}\text{C}$. These results suggest that late-LIA cooling at this tropical Southern Hemisphere site was smaller in magnitude than many Northern Hemisphere reconstructions. Shell $\delta^{13}\text{C}$ exhibited pronounced seasonal variability, consistent with the precipitation-related hydroclimatic seasonality. Statistical analyses reveal pronounced two- to three-year periodicities in both SST and hydroclimatic variability, with more frequent El Niño-like events in the late 1700s and stronger La Niña-like conditions in the early 1800s. This 30-year *Tridacna* record therefore provides a rare seasonal marine archive for evaluating Southern Hemisphere climate variability during the terminal LIA.

1. Introduction

Since the onset of the Industrial Revolution in the mid-19th century, anthropogenic greenhouse gas emissions have led to an unprecedented rise in global temperatures, marking the beginning of modern climate warming (IPCC et al., 2023). Understanding the natural variability of the

climate system prior to this rapid warming is critical for assessing the full extent and trajectory of anthropogenic climate change. One of the most significant pre-industrial cooling periods was the Little Ice Age (LIA), which spanned from the early 1300s to the 1850s. Compared to present-day global average temperatures under the influence of ongoing warming, mean temperatures at the end of the LIA were approximately

* Corresponding author at: School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Melbourne, Australia.

E-mail address: amy.prendergast@unimelb.edu.au (A.L. Prendergast).

<https://doi.org/10.1016/j.gloplacha.2026.105717>

Received 31 March 2026; Received in revised form 13 August 2026; Accepted 8 September 2026

Available online 13 September 2026

0921-8181/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1.0 to 1.5 °C lower based on multi-proxy palaeoenvironmental reconstructions (IPCC et al., 2023; Mann et al., 1998; PAGES 2k Consortium, 2019). Although both the LIA and subsequent industrial-era warming are often considered global phenomena, the majority of palaeoenvironmental reconstructions documenting these events have been derived from high-latitude and continental archives in the Northern Hemisphere (Hendy et al., 2002; PAGES2k Consortium et al., 2017). Consequently, there is a significant gap in our understanding of how low-latitude tropical and subtropical marine systems in the Southern Hemisphere responded to late LIA climate variability, particularly in marine systems. Developing high-resolution palaeoenvironmental records from low-latitude tropical and subtropical marine environments in the Southern Hemisphere is therefore crucial to refining our understanding of the spatial extent, climatic impacts, and human-environmental interactions of both the LIA cooling and the subsequent warming associated with the Industrial Revolution.

Sclerochronology provides an important means to generate palaeoclimatic data that can inform high-resolution palaeoenvironmental reconstructions (Butler and Schöne, 2017; Oschmann, 2009; Peharda et al., 2021; Trofimova et al., 2020). Where palaeoenvironmental data can be reconstructed from archaeological samples, records can extend many years into the past, providing new insights into long-term interactions between the dynamics of the climate and human activities (Peharda et al., 2021; Prendergast et al., 2018).

The shells of the *Tridacna* spp., also known as the giant clams, provide an excellent archive of palaeoenvironmental data. This species is the world's largest bivalve mollusc, measuring up to 120 cm in length and weighing up to 230 kg (Mies et al., 2017; Rosewater, 1965). *Tridacna* has a widespread distribution in the warm shallow seas of the Indo-Pacific region (Othman et al., 2010) and has relatively high growth rates with increments produced within the shell at monthly or even daily intervals across long (more than 60 years) lifespans (Dong et al., 2025b; Warter et al., 2015; Watanabe et al., 2004; Watanabe and Oba, 1999). This enables the comparison of growth patterns with paired geochemical records at very high temporal resolutions (Dong et al., 2025a; Sano et al., 2012; Watanabe and Oba, 1999; Yan et al., 2020). Analysis of the geochemical composition of *Tridacna* shells has now been used to reconstruct palaeoenvironmental records of sea surface temperature (SST) (Aharon and Chappell, 1986; Arias-Ruiz et al., 2017; Aubert et al., 2009; Elliot et al., 2009; Reuter et al., 2022; Wang et al., 2022; Yan et al., 2015; Yan et al., 2014), sea surface salinity (SSS) (Ayling et al., 2015; Batenburg et al., 2011; Watanabe and Oba, 1999), dissolved inorganic carbon (DIC) (Elliot et al., 2009; Romanek and Grossman, 1989), insolation (Ayling et al., 2015; Hori et al., 2015; Sano et al., 2012), rainfall (Arias-Ruiz et al., 2017; Batenburg et al., 2011), marine primary productivity (Elliot et al., 2009; Komagoe et al., 2018; Warter et al., 2015), extreme weather events (Komagoe et al., 2018; Yan et al., 2020; Zhao et al., 2023) and variations in the El Niño-Southern Oscillation (ENSO) phenomenon (Arias-Ruiz et al., 2017; Duprey et al., 2014; Duprey et al., 2012; Hu et al., 2020; Liu et al., 2019; Zhou et al., 2022) across multiple decades.

Here, we present a 30-year ultra-high-resolution seasonal proxy record of palaeoenvironmental variability derived from a *Tridacna gigas* collected from the northern Great Barrier Reef (GBR), Australia. The shell grew during the last phase of the LIA, just prior to the onset of anthropogenic warming associated with the Industrial Revolution and the European colonisation of northern Queensland in the 1850s. We applied stable isotope proxies, including $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ from both inner and outer shell layers, to reconstruct sea surface temperature, precipitation-related hydroclimatic variability, and local ENSO-like variability. These reconstructions provide a high-resolution 30-year window into environmental conditions at Jiigurru, contributing site-specific Southern Hemisphere evidence for the terminal phase of the LIA. As the first study to employ a sclerochronology archive to capture seasonal-scale climate dynamics immediately before the rise of industrial-era warming, this study helps fill a major spatial and temporal

gap in current palaeoclimate reconstructive records. Our findings contribute to generating a more comprehensive understanding of natural climate variability and improve contextualization of present-day climate change, thereby supporting future adaptation strategies in a warming world.

2. Materials and methods

2.1. Sample site

A single-valve of a deceased *Tridacna gigas* (sample 21GC) was collected in 2015 from a coral reef (14° 40' 48.32" S, 145° 26' 42.09" E) in the lagoon of Jiigurru (Lizard Island Group), on the midshelf region of the Great Barrier Reef, Australia (Fig. 1). Jiigurru and the adjacent islands in this Island Group enclose a large lagoon, with extensive fringing reefs and abundant *Tridacna* populations. Jiigurru plays and has played an important role in Aboriginal culture as a place of socio-cultural significance for ceremonies and gatherings (Lambrides et al., 2020). The oldest occupation layers in shell middens of the Lizard Island Group date to 6500 years ago, making Jiigurru the oldest offshore island occupation in the Great Barrier Reef (Ulm et al., 2024; Ulm et al., 2019). Many of the shell middens in the Lizard Island Group contain abundant *Tridacna* shells (Alidoostsalimi et al., 2026; Alidoostsalimi et al., 2025; Kneppers et al., 2024; Lambrides et al., 2020).

Records of *in situ* modern temperature and salinity from 1995 to 2015 were obtained from an automated marine weather and oceanographic station, operated by the Australian Institute of Marine Science (AIMS) (Australian Institute of Marine Science, 2017). This station was situated within tens of metres of the shell collection location. Weather station sensors were deployed at 2.6 m water depth, approximately the same depth as the living environment of *Tridacna*. During the austral summer (December to February), SST averaged around 29 °C, whereas during the winter (June to August), SST averaged around 24 °C (Fig. 2). The highest rainfall at Jiigurru occurred from January to March, and the driest months were July to September (Fig. 2).

2.2. *T. gigas*

Tridacna spp., also known as giant clams, are the most iconic marine bivalves on coral reefs because of their massive shell and brilliantly coloured mantles. The *Tridacna* have a wide habitat in the warm seas of the Indo-Pacific region and prefer to inhabit shallow water from 2 to 10 m with temperatures between 25 °C and 30 °C (Othman et al., 2010; Richard, 1992; Rosewater, 1965). As the largest *Tridacna*, *T. gigas* can reach 120 cm in length and weigh more than 230 kg, owing to rapid annual incremental growth of 2 to 6 mm (sometimes up to 10 mm) and lifespans of over 60 to 100 years (Dong et al., 2025b; Elliot et al., 2009; Warter et al., 2015; Watanabe et al., 2004; Watanabe and Oba, 1999). The rapid growth rate of *Tridacna* creates distinct growth bands, with a wide bright and narrow dark couplet forming a single yearly increment (Fig. 3b) that corresponds to growth during warm and cold months, respectively (Arias-Ruiz et al., 2017). The annual growth increments can be observed with the naked eye or enhanced with stains such as Mutvei's solution (Komagoe et al., 2018). Annual and daily increments can be observed using optical or high-resolution microscopy, allowing *Tridacna* shells to preserve environmental variability from daily to seasonal scales (Arias-Ruiz et al., 2017; Duprey et al., 2014; Gannon et al., 2017; Yan, 2020). Compared with other species used for sclerochronology to extract archives of climate proxies, *Tridacna* shells hold great potential for reconstructions at sub-daily to seasonal resolution (Arias-Ruiz et al., 2017; Ayling et al., 2015; Hori et al., 2015; Warter and Müller, 2017; Yan, 2020).

2.3. Sample preparation

Shell 21GC was 58 cm long, 30 cm wide and 20 cm high, with the

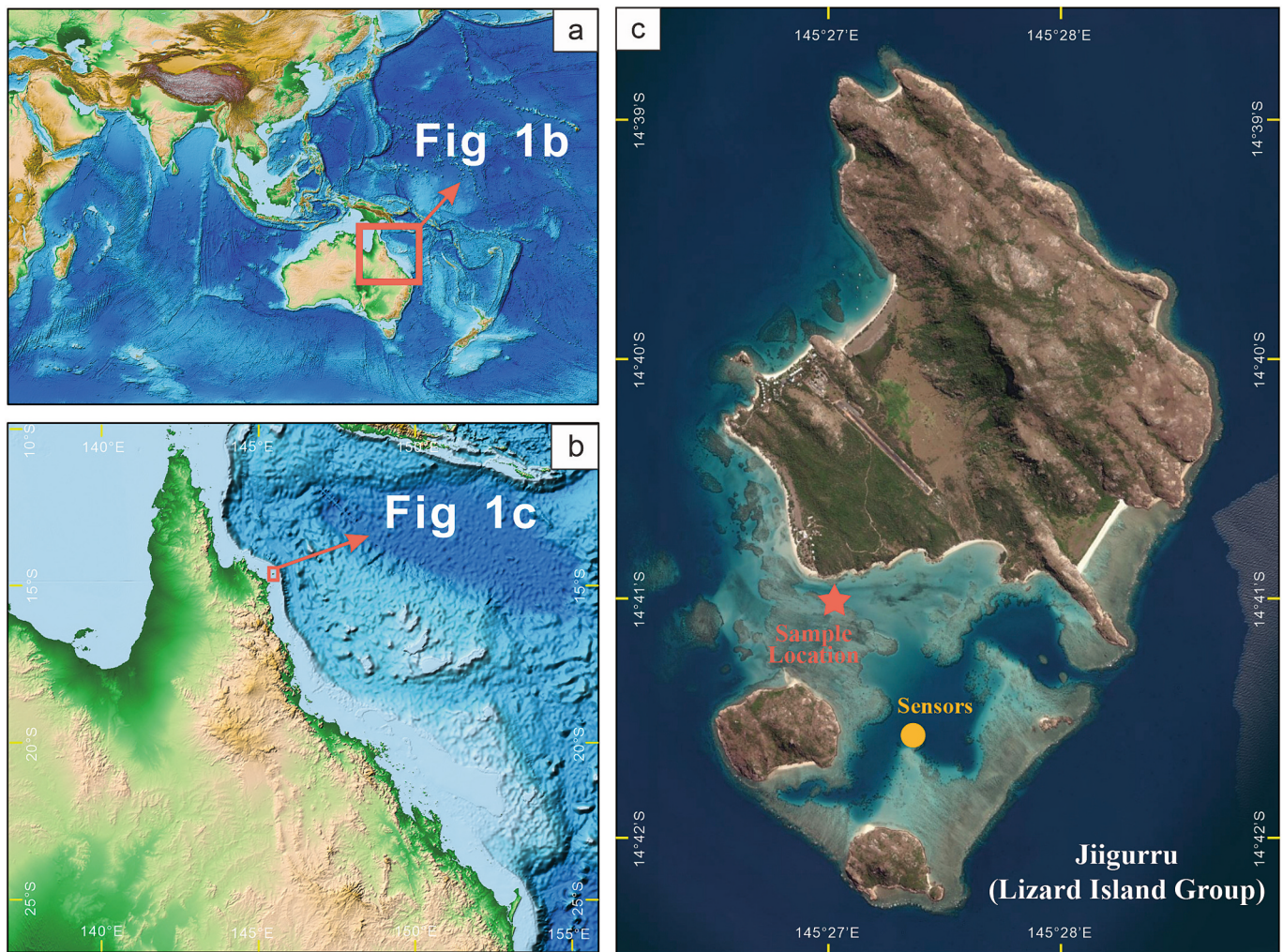


Fig. 1. Map with sampling locations. (a) Topographic map of the Indo-Pacific. (b) Map of GBR, Northern Australia. (c) Satellite map of Jiigurru (Lizard Island Group) and sample location with red star. DEM maps (a) and (b) adopted from <http://www.data.ac.cn/map/> and satellite map (c) are adopted from <https://earth.google.com>. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thickest shell deposition reaching 9 cm (Fig. 3a). A total of 10 parallel sample sections, each approximately 1.5 cm thick were cut along the maximum growth axis from the umbo to the ventral margin. The sections were ground and manually polished with diamond-embedded pads with successive grit sizes of 60, 120, 200 and 1800. The annual growth increments on both the inner and outer shell layers were clearly visible to the eye after the polishing (Fig. 3b). Two adjacent sections taken from along the maximum growth axis were used in this study, one for geochemical analysis and the other for microscopy and radiometric dating.

The inner shell section used for geochemical analysis was cut into smaller blocks and then subjected to finer grinding and polishing, making it suitable for observation under the optical microscope. The section was cut into five ~1 mm thick pieces using a rock saw, with overlapping parts to prevent information loss caused by saw-blade thickness. A Struers EpoFix epoxy was used to mount the samples onto slides. The sections mounted on the slides then underwent fine polishing using a Struers LaboPol-30 auto grinding/polishing machine, with 15 μm diamond paste for grinding, and 6, 3 and 1 μm diamond paste for polishing.

Two milling systems were used to obtain the powdered aragonite samples from the inner shell and outer shell. The samples from the inner shell were milled using a New Wave Micromill, and the samples from the outer shell were obtained using a Taig CNC Micromill. With both

methods, a trench was milled along the maximum growth axis of the shell and followed the same procedure: drill bit width of 600 μm , a trench depth of 500 μm with a length of 8 mm and a sampling interval of 300 μm . The milling trench was oriented perpendicular to the increment patterns to access isochronous shell samples.

Following this protocol, approximately 2.5 mg of fine homogeneous aragonite powder was generated from each sample for stable isotope analysis. A total of 784 powdered samples were collected, comprising 307 samples from the inner shell layer and 477 samples from the outer shell layer.

2.4. Radiocarbon dating

AMS ^{14}C dating was undertaken to determine the living period of the shell, with measurements performed at the Centre for Accelerator Science, at the Australian Nuclear Science and Technology Organisation (ANSTO). Three samples representing the youngest, middle and oldest portions of the inner shell growth profile were collected at positions 0, 45, and 90 mm along the profile of the inner shell.

2.5. Optical microscopy observation

Daily growth increments (DGIs) were observed using a Carl Zeiss M1m Axio-Imager optical microscope, paired with TrackWorks

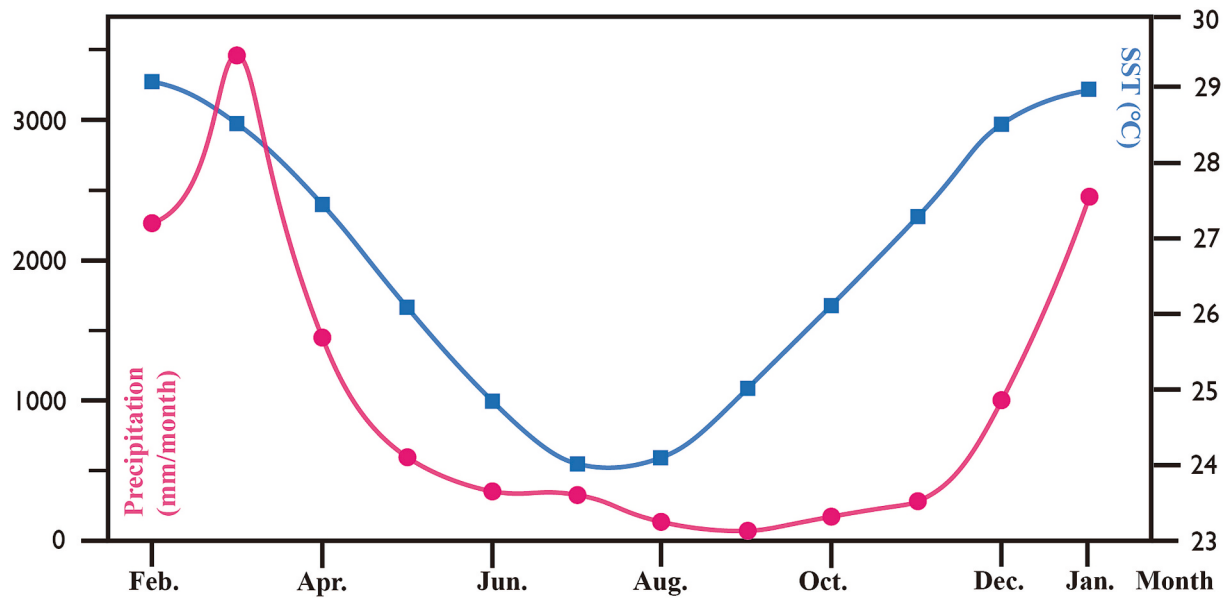


Fig. 2. Long-term averaged monthly *in situ* instrumental records at Jiigurru (Lizard Island Group) from 1995 to 2015, including precipitation (pink line and circles) and SST (blue line and squares). Modern monitoring data from the [Australian Institute of Marine Science \(2017\)](#). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

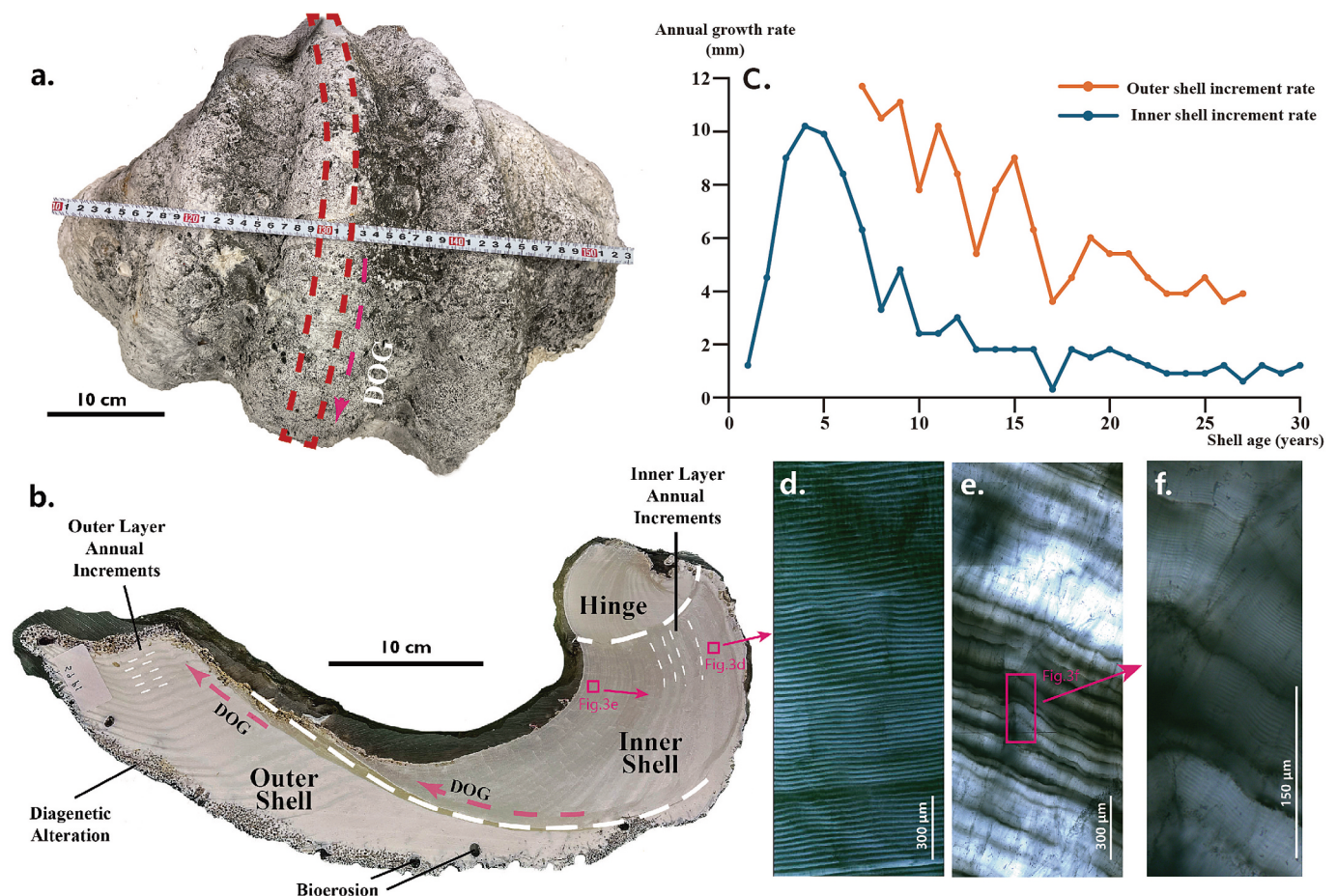


Fig. 3. Shell section and increments. (a) The *T. gigas* valve shell. The red dashed rectangle shows the location of section for geochemical analysis. (b) The cross-section of the shell showing the hinge, inner shell and outer shell locations. Annual increments are shown with dashed lines on the section. The direction of growth (DOG) is represented with pink dashed lines and arrows. (c) Annual increment growth rate for the inner (blue) and outer shells (orange). (d) Ontogenetically juvenile inner shell daily increment. (e) Ontogenetically old inner shell daily increment. (f) Magnified ontogenetically old inner shell daily increments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

software, developed by the Melbourne Thermochronology Group at the Trace Analysis for Chemical, Earth and Environmental Science (TrACEES) platform at the University of Melbourne (UoM). The finely ground and polished inner shell slides were observed under transmitted light and photographed at 10 $\times$ magnification using a 4MP iDS camera. Micrometric growth patterns were visible under transmitted light, with the alternating dark increments and bright growth lines clearly resolved (Fig. 3d, e & f). Following the shell growth direction, a single coupled dark-bright band pair was considered a growth increment deposited during a single day (Aharon and Chappell, 1983; Arias-Ruiz et al., 2017). Due to the limited field of view under the microscope, we used the Mosaic function in TrackWorks software to stitch together different visual fields. Each slide was independently counted three times by three different individuals to test for count reliability. The results are reported as the average of nine counts from three individuals for each slide.

2.6. Geochemical analysis

An Analytical Precision AP2003 continuous-flow stable isotope ratio mass spectrometer (IRMS) at the University of Melbourne was used to analyse $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. The milled samples from the inner shell ($n = 307$) and outer shell ($n = 477$) layers were weighed into exetainer vials (mass range: 0.55–0.65 mg) and sealed with septum caps. The exetainers were then placed on a hot block (set to 70 $^{\circ}\text{C}$) and purged with high-purity helium to remove ambient air. After purging, approximately 0.05 mL of $\sim 105\%$ orthophosphoric acid was injected into the vials to liberate CO_2 , and the resulting gas was analysed in the mass spectrometer. All results are reported relative to the Vienna Pee Dee Belemnite (VPDB) international standard. Three internal standard samples were normalized to this scale, NEW 1 ($\delta^{13}\text{C} = 2.4\text{‰}$, $\delta^{18}\text{O} = -2.46\text{‰}$), NEW 12 ($\delta^{13}\text{C} = -3.79\text{‰}$, $\delta^{18}\text{O} = -9.72\text{‰}$) and Estremoz ($\delta^{13}\text{C} = 1.57\text{‰}$, $\delta^{18}\text{O} = -6.01\text{‰}$), which were previously calibrated using the international standards NBS-18 and NBS-19. Analytical uncertainty for $\delta^{13}\text{C}$ was 0.05 ‰ and for $\delta^{18}\text{O}$ was 0.10 ‰, respectively.

2.7. Data processing and statistical analysis

Anomalous data points, including jumps and outliers, were removed during data processing. For isotope data, the points 21GC-026 and 21GC-281 from the inner shell were removed as they returned results exceeding two standard errors of uncertainty. Point 21GC-O-308 of the outer shell was also removed as it was an anomalous single-point jump.

We applied spline interpolation using QAnalySeries, a widely used environmental data analysis program in the field of sclerochronology, for converting sampling distance coordinates to chronological coordinates, and transform all data to the same monthly resolution (Kotov and Pälike, 2018; Paillard et al., 1996). Resampling can reduce potential biases related to variability in growth rates (Wanamaker et al., 2011; Yan et al., 2015). Wavelet analyses were performed using the time-series analysis software, Acycle (Li et al., 2019), following Torrence and Compo (1998). The Multi-Taper Method analysis was conducted by another analysis software, Past (Hammer et al., 2001).

2.8. ENSO-like events identification

In this study, local ENSO-like events were identified from the reconstructed northern GBR SST anomalies using criteria adapted from the National Oceanic and Atmospheric Administration's (NOAA) Oceanic Niño Index (ONI) (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/). The standard ONI is the 3-month running mean of SST anomalies in the Niño-3.4 region (5 $^{\circ}\text{N}$ –5 $^{\circ}\text{S}$, 120 $^{\circ}$ –170 $^{\circ}\text{W}$), with a $\pm 0.5\text{ }^{\circ}\text{C}$ threshold and a persistence criterion of at least 5 consecutive overlapping seasons. In order to reflect the austral summer peak season of ENSO variability, we further required that the persistence window explicitly include November–December of year 0 and January of year 1 (NDJ). Given the higher latitude and stronger SST seasonality

of the northern GBR site relative to the Niño-3.4 region, we supplemented the adapted ONI criteria with a local strength metric: within each event window identified using these criteria, a strong local ENSO-like response was flagged when the absolute z-score of the deseasonalised proxy anomaly exceeded 1σ . This dual criterion retains the threshold and persistence structure of the standard ONI, but the resulting events represent local ENSO-like responses in the northern GBR record.

3. Results

3.1. Absolute age of the shell

The AMS conventional ^{14}C ages for 21GC-Outer, 21GC-Mid and 21GC-Inner were 460 ± 25 , 500 ± 25 and 510 ± 25 yr BP (Table 1). The results were calibrated using OxCal (v.4.4) (Bronk Ramsey, 2009) and the Marine20 calibration dataset (Heaton et al., 2020), using the regional ΔR of -197 ± 56 yr recommended by Ulm et al. (2024). The calibrated median age results indicate that the clam lived from approximately 1785–1827 CE, aligning with the end of the LIA.

3.2. Sclerochronology results

The inner and outer shell layers were composed of high-purity aragonite with no evidence of alteration or secondary calcite alteration. Microscopic observations showed no growth breaks and no clear seasonal increment-rate trend between warm and cold seasons. However, annual increment width varied substantially with ontogenetic age, increasing from ~ 4 mm/yr to ~ 10 mm/yr during the juvenile phase, between shell ages 1 and 4 years (Fig. 3c). From the age of 4 onwards, there was a significant decline in width, with the size of increments dropping to approximately 2 mm/yr by the age of 10 (Fig. 3c & d). After this time, the width of annual increments remained at an average of 2 mm/yr, and declined to around 1 mm/yr from the age of 20 (Fig. 3c). At this age, growth increments were more difficult to resolve (Fig. 3e & f); therefore, contemporaneous DGIs from different parts of the shell were used to identify clearer counting sections. In some cases, the number of DGIs was estimated. In total, we identified approximately 10,906 DGIs from the cross-section of the shell, suggesting a lifespan of 29.86 years (365.25 days/yr). Additionally, the $\delta^{18}\text{O}$ profile of the inner shell showed 29 complete annual variations and one incomplete variation in the most juvenile portion. Together, these results indicate that the clam was 30 years old at death.

Table 1

Radiocarbon dating results of the studied giant clam shell. Three samples from 21GC-Outer, 21GC-Mid and 21GC-Inner were collected at positions 0 mm, 45 mm, and 90 mm along the inner shell profile, representing the youngest to the oldest ontogenetic growth, respectively. The results were calibrated by using OxCal (v.4.4) (Bronk Ramsey, 2009) and the Marine20 calibration dataset (Heaton et al., 2020), with the regional ΔR of -197 ± 56 yr recommended by Ulm et al. (2024). The calibrated median age results indicate that the studied shell lived from approximately 1785–1827 CE.

Sample ID	$\delta^{13}\text{C}$	percent Modern Carbon	Conventional Radiocarbon age	Median Modelled Age
	per mil	pMC (1 σ error)	yr BP (1 σ error)	CE
21GC-Outer	1.9 +/- 0.1	94.41 +/- 0.27	460 +/- 25	1827
21GC-Mid	2.5 +/- 0.1	93.98 +/- 0.27	500 +/- 25	1795
21GC-Inner	1.8 +/- 0.1	93.86 +/- 0.27	510 +/- 25	1785

3.3. Stable isotope results

$\delta^{18}\text{O}$ values from both the inner and outer shell layers exhibited clear seasonal variability (Fig. 4). However, the amplitude of inner shell $\delta^{18}\text{O}$ seasonal variation declined toward the ontogenetically older portion of the shell. The $\delta^{18}\text{O}$ of the inner shell ranged from -1.72‰ to 0.12‰ (mean = -0.68‰ , $n = 307$), whereas the outer shell ranged from -1.57‰ to 0.28‰ (mean = -0.63‰ , $n = 477$).

Although there was no obvious annual $\delta^{13}\text{C}_{\text{Shell}}$ cyclicity in the inner shell layer (Fig. 5), $\delta^{13}\text{C}_{\text{Shell}}$ from the outer shell layer displayed clear annual patterns with inflection points offset from those in $\delta^{18}\text{O}$ (Figs. 4 & 5). Values of $\delta^{13}\text{C}$ fluctuated between 2.01‰ and 2.74‰ (mean = 2.32‰) in the inner shell and between 2.00‰ and 4.23‰ (mean = 3.72‰) in the outer shell layer. The $\delta^{13}\text{C}_{\text{Shell}}$ values remained in a stable range, and there was no noticeable ontogenetic trend in the $\delta^{13}\text{C}_{\text{Shell}}$ values.

3.4. Converting data to equal chronological intervals

Previous studies have demonstrated that $\delta^{18}\text{O}$ profiles of *Tridacna* shells exhibit annual cyclicity, both in the inner and outer shell layers (Aharon, 1991; Duprey et al., 2014; Elliot et al., 2009; Wang et al., 2022; Warter et al., 2015). This was also the case for shell 21GC. However, the significant growth-rate difference between the ontogenetically juvenile and the ontogenetically older portion of the inner shell ($\sim 10\text{ mm/yr}$ to $\sim 2\text{ mm/yr}$) resulted in significant variability in the width of each $\delta^{18}\text{O}$ annual waveform obtained from equidistant drilling. This poses a challenge for reconstructing monthly to annual resolution environmental records from the inner shell and for comparing the inner and outer shell records.

To address this challenge, we regarded each trough of the time series of $\delta^{18}\text{O}$ in the inner shell as a marker to divide each annual cycle. We then resampled the equidistant sampling intervals to create a time series with 12 points per year (monthly resolution) for both the inner and outer shell layers by using the spline interpolation function in QAnalySeries (Fig. 4) (Kotov and Pälike, 2018; Paillard et al., 1996; Wang et al., 2022; Welsh et al., 2011; Zhao et al., 2023). The rate of deposition of increments may differ between summer and winter, which could confound estimates of geochemical signals if sampling is equidistant along the shell transect (Johnson et al., 2022; Schöne, 2008). However, microscopic increment observations of shell 21GC showed no noticeable seasonal growth-rate trend between warm and cold seasons. Therefore, equidistant sampling is unlikely to have introduced a systematic seasonal bias in this shell. The main effect of equidistant sampling was instead related to ontogenetic growth-rate decline. In the ontogenetic older inner shell, slower growth meant that each physical sampling interval integrated a longer period of shell formation, resulting in reduced temporal resolution and smoothing of the $\delta^{18}\text{O}$ seasonal amplitude. To minimize this effect, the isotope profiles were converted from distance coordinates to chronological coordinates and resampled to monthly resolution using spline interpolation in QAnalySeries. In addition, the smoothed ontogenetic older inner shell $\delta^{18}\text{O}$ record was excluded from the palaeoenvironmental reconstruction.

4. Discussion

4.1. Comparison of inner and outer shell records: Strengths, limitations and implications for palaeoenvironmental reconstruction

The resampled $\delta^{18}\text{O}$ profile of the inner shell revealed 22 distinct annual cycles; however, $\delta^{18}\text{O}$ variations from 22 to 30 years of age had a much narrower range than those in the first 22 years of growth (Fig. 4a). This likely reflects the combination of fixed-width equidistant milling and slower shell growth in older increments, which caused each sample to integrate a longer period of carbonate deposition and smooth the seasonal $\delta^{18}\text{O}$ peaks and troughs (Ayling et al., 2015). The $\delta^{18}\text{O}$ signal

during the first year of growth was also poorly resolved, potentially reflecting slow juvenile growth or early ontogenetic effects. To minimize these uncertainties, only $\delta^{18}\text{O}$ data from shell age 1 to 22 years were used for subsequent palaeoenvironmental reconstructions.

The resampled $\delta^{18}\text{O}$ profile of the outer shell showed more uniform seasonal variation across the analysed growth interval, with 22.5 annual cycles and no obvious decline in seasonal amplitude (Fig. 4a). However, the outer shell layer of archaeological and sub-fossil *Tridacna* is generally more vulnerable to surface erosion, microboring and post-depositional alteration because it is exposed at the seawater interface. Furthermore, distinguishing the outer shell increments from the inner shell increments and sampling the juvenile outer shell increments is challenging, as the boundary between these layers is not always clearly defined (Fig. 3b) (Arndt et al., 2023; Hu et al., 2020; Mei et al., 2018; Reuter et al., 2022). Shell 21GC experienced minimal seawater erosion or diagenesis, with no recrystallisation and only 1.2 cm of surface alteration identified near the ventral margin (Fig. 3b). After identifying the annual growth increments on the outer shell and aligning the $\delta^{18}\text{O}$ profile with the inner shell, we determined that the available geochemical records from the outer layer span approximately shell age 6–27.5 years, after excluding the incomplete first and last half-year segments.

Given these results, the geochemical records from the inner shell and outer shell layers each have distinct advantages and limitations. For the inner shell: (1) it is usually well preserved with no obvious alteration; (2) it can provide a relatively complete ontogenetic record; (3) it offers ultra-high resolution records (weekly to fortnightly intervals) from the juvenile increments; (4) however, the slower rate of growth in the ontogenetically older increments results in reduced temporal resolution and smoothed seasonal proxy variability. For the outer shell: (1) the annual increment pattern is easily discernible by eye, facilitating assessments of growth rates and sampling intervals before drilling; (2) the growth rate of the outer shell is relatively stable, enabling easier acquisition of data with consistent resolution; (3) however, the outer shell records are often incomplete due to alteration, erosion and/or damage occurring at the interface with seawater and post-depositionally for archaeological and sub-fossil shells. This systematic comparison provides the basis for combining the better-preserved and higher-resolution portions of both shell layers, producing a longer, more continuous and less smoothed $\delta^{18}\text{O}$ series for SST reconstruction.

4.2. $\delta^{18}\text{O}$ offset between the inner shell and the outer shell

The resampled $\delta^{18}\text{O}$ data derived from inner and outer shell layers showed very similar seasonal variability from shell age 6 years (the youngest visible records in the outer layer) to the ontogenetically oldest unsmoothed records from the inner shell at age 22 years. After comparing the average monthly $\delta^{18}\text{O}$ values between shell ages 6 and 22 years in the inner and outer shell layers, we found that the monthly $\delta^{18}\text{O}$ relationship can be expressed by the following linear regression equation (Fig. 4b):

$$\delta^{18}\text{O}_{\text{Inner shell}} = 1 \times \delta^{18}\text{O}_{\text{Outer shell}} - 0.21 \pm 0.02 \quad (1)$$

In this regression, the monthly resolved $\delta^{18}\text{O}$ values of the inner and outer shell layers show a very strong correlation ($R^2 = 0.96$, $p < 0.001$), suggesting they are highly synchronised, with an intercept of -0.21 indicating a consistent negative offset of 0.21‰ for the inner shell compared to the outer shell (Fig. 4c).

Other studies have recorded offsets of $\delta^{18}\text{O}$ values between inner and outer layers of *Tridacna* shells. Earlier work by Elliot et al. (2009) and Killam et al. (2020) both reported $\delta^{18}\text{O}$ ratios that were more positive by 0.2 to 0.4‰ in the outer shell compared to the age equivalent inner shell layers. Offsets ranging from 0.2 to 0.6‰ between shell layers have also been reported in other species of bivalve (Bajnai et al., 2018; Letulle et al., 2023). Although some studies have suggested that *Tridacna* spp.

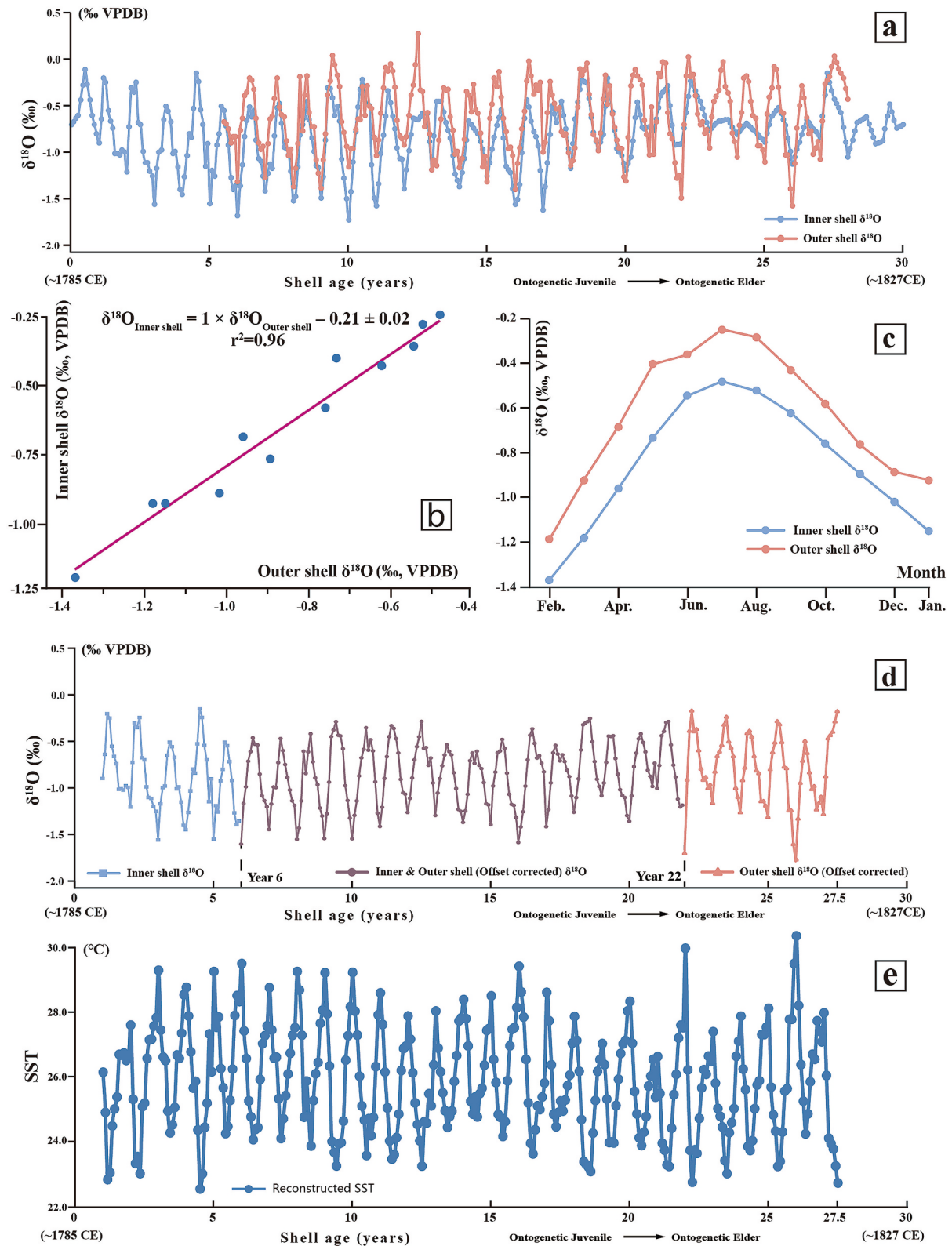


Fig. 4. Monthly resolved $\delta^{18}\text{O}$ profiles and the reconstructed SST in LIA. (a) Monthly resolved $\delta^{18}\text{O}$ from the inner shell (light blue) and outer shell (pink). (b) Linear regression (red line) between values of $\delta^{18}\text{O}$ (blue spots) in the inner and outer shell of a giant clam. (c) Monthly values of $\delta^{18}\text{O}$ showing offset between the inner (light blue) and outer shell (pink). (d) Combined $\delta^{18}\text{O}$ from shell ages 0.5 to 6 years old is from the inner shell (light blue), 6 to 22 years old is from the average inner shell and offset corrected outer shell (purple) and 22 to 27.5 years old is from offset corrected outer shell (pink). Calendar ages in brackets on the x-axis represent the approximate calibrated ^{14}C age range of shell 21GC, rather than precise absolute ages for individual growth increments. (e) Reconstructed LIA SST based on $\delta^{18}\text{O}_{\text{shell}}$ of the studied giant clam of 27.5 years shell age. Data are plotted as a function of ontogenetic age from younger to older. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

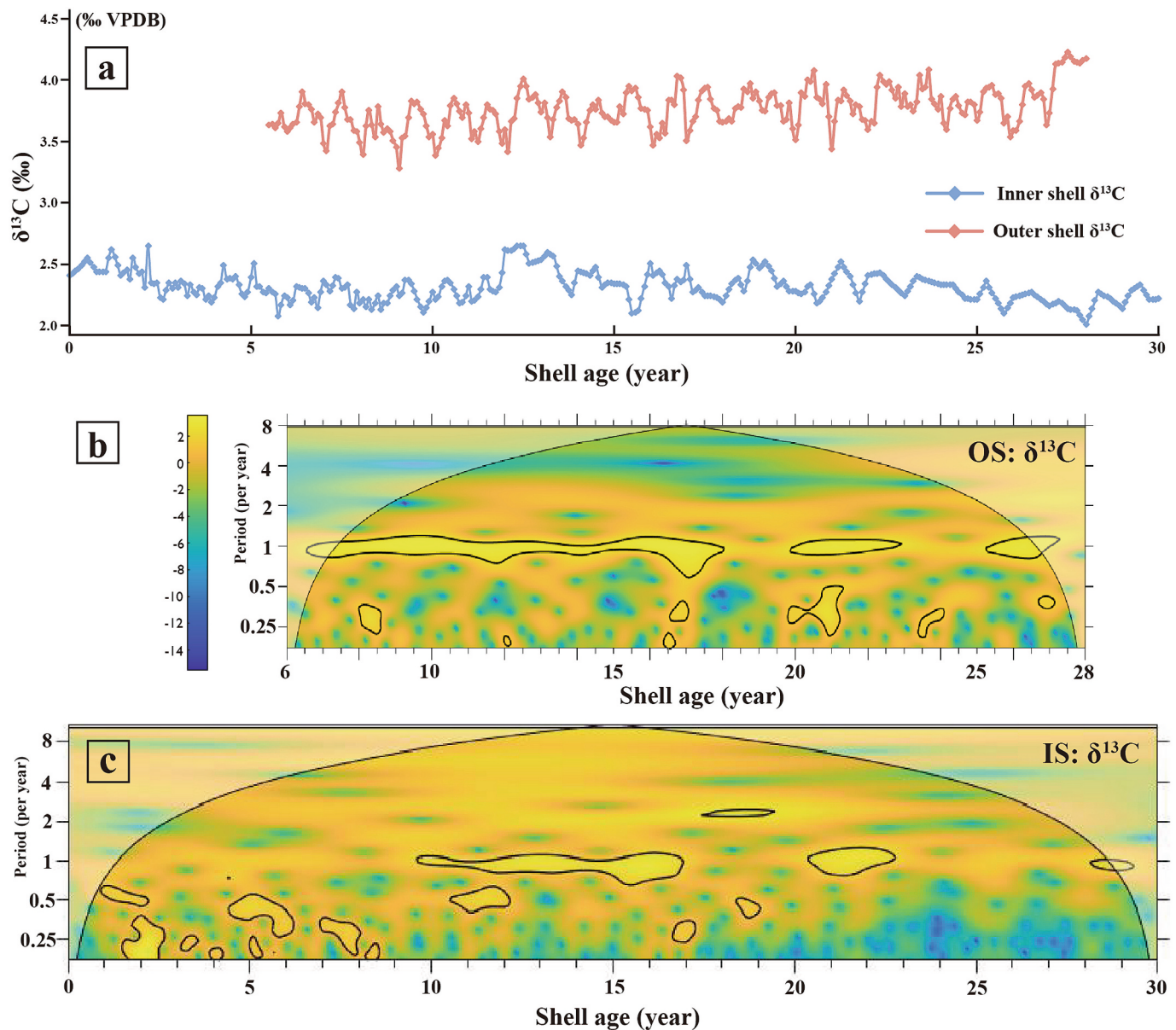


Fig. 5. Monthly resolved $\delta^{13}\text{C}$ profiles and the wavelet analysis results of the inner shell and outer shell. (a) Monthly resolved $\delta^{13}\text{C}$ from the inner shell (light blue) and outer shell (pink). (b) Wavelet analysis of the outer shell $\delta^{13}\text{C}$ from shell age 6 to 28 years old. (c) Wavelet analysis of the inner shell $\delta^{13}\text{C}$ from shell age 0 to 30 years old. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

precipitate aragonite in oxygen isotope equilibrium with seawater (Morissette et al., 2023; Romanek et al., 1987), our observations of a slight offset between the inner shell and the outer shell suggest that this is not necessarily the case. Compared with the outer extrapallial fluid (EPF), the inner EPF between the inner shell and the soft tissue of the clam may be alkalised by perhaps 0.5 pH units, which can influence the transport and speciation of CO_3^{2-} during inner shell formation (McConnaughey and Gillikin, 2008). The offset may also be related to differences in mineralisation between the inner and outer shell layers, since the outer layer is composed of crossed-lamellar/dendritic aragonite while the inner layer is prismatic (Fousiya et al., 2024). These contrasting shell fabrics may reflect differences in nucleation, crystal growth pathways, organic matrix control, and calcification rates between the two shell layers. Such differences could promote layer-specific kinetic isotope effects, particularly if aragonite precipitation does not occur under full isotopic equilibrium with the calcifying fluid. Experimental and modelling studies of carbonate precipitation have shown that oxygen isotope fractionation can be influenced by precipitation

kinetics, pH-dependent carbonate speciation, and departures from isotopic equilibrium (Wang et al., 2013; Watkins et al., 2013). Similar biological and kinetic isotope effects have also been documented in bivalve aragonite, including larval aragonite (Owen et al., 2008). Therefore, the observed $\delta^{18}\text{O}$ offset is unlikely to reflect a single mechanism, but may instead result from the combined influence of EPF chemistry, shell microstructure, calcification kinetics, and layer-specific vital effects. However, there is also evidence that offsets can vary among different locations.

For example, Elliot et al. (2009) analysed the $\delta^{18}\text{O}$ composition of the inner and outer shell layers of a *T. gigas* shell (*Tg-Palm*) collected from Great Palm Island on the inner GBR. The monthly $\delta^{18}\text{O}$ values of *Tg-Palm* produce the following linear regression equation:

$$\delta^{18}\text{O}_{\text{Inner shell}} = 1 \times \delta^{18}\text{O}_{\text{Outer shell}} - 0.35 \pm 0.02 \quad (2)$$

This indicates that the monthly resolved $\delta^{18}\text{O}$ values from inner and outer layers of *Tg-Palm* are strongly and significantly correlated ($R^2 =$

0.95, $p < 0.001$). However, the *Tg-Palm* $\delta^{18}\text{O}$ offset of 0.35 ‰ is slightly larger than the offset observed in shell 21GC. This variation in $\delta^{18}\text{O}$ offset between studies could reflect differences in the range of seasonal temperatures experienced by clams at the two locations. *Tg-Palm* was collected from a site approximately 4° of latitude, or ~ 400 km, south of Jiigurru, where the annual temperature range is approximately 8 °C (range from 22 to 30 °C) compared to approximately 5 °C for Jiigurru (range from 24 to 29 °C) (Aharon, 1991; Australian Institute of Marine Science, 2017; Elliot et al., 2009). This larger annual temperature range may contribute to the larger $\delta^{18}\text{O}$ offset between inner and outer shell layers in the Great Palm Island specimen.

In summary, the existing evidence indicates that there is a constant offset between the $\delta^{18}\text{O}$ values of the inner and outer shell layers, facilitating the conversion and comparison of $\delta^{18}\text{O}$ data between these layers. This enables us to combine the best preserved and highest resolution $\delta^{18}\text{O}$ records from both the inner and outer shell layers, resulting in a longer, more continuous, and less smoothed $\delta^{18}\text{O}$ dataset spanning most of the clam's lifespan. However, the mechanisms controlling the magnitude of this offset remain uncertain. Further investigation of *Tridacna* shells from different environmental settings, combined with microstructural and geochemical observations, is required to better determine the relative roles of EPF chemistry, shell microstructure, calcification kinetics, and layer-specific vital effects.

4.3. SST reconstruction in the LIA

Many studies have shown that $\delta^{18}\text{O}$ profiles from modern *Tridacna* shells exhibit strong correlations with records of SST (Aharon, 1991; Arias-Ruiz et al., 2017; Ayling et al., 2015; Duprey et al., 2015; Elliot et al., 2009; Fousiya et al., 2022; Ma et al., 2020; Wang et al., 2022). Consequently, *Tridacna* $\delta^{18}\text{O}$ has been widely used for palaeo-SST reconstruction across Indo-Pacific settings, most commonly using the inner shell layer (Aharon, 1983; Aubert et al., 2009; Batenburg et al., 2011; Elliot et al., 2009; Romanek and Grossman, 1989; Watanabe et al., 2004; Welsh et al., 2011; Yan et al., 2014). However, we combined $\delta^{18}\text{O}$ records from inner and outer shell layers to reconstruct SSTs, with a 0.21 ‰ offset applied to convert $\delta^{18}\text{O}_{\text{Outer shell}}$ to $\delta^{18}\text{O}_{\text{Inner shell}}$ (as described above). As the record from the outer shell began at 6 years of age and the inner shell record after 22 years of age was smoothed, the combined $\delta^{18}\text{O}$ dataset was based on: age 0.5 to 6 years = inner shell; age 6 to 22 years = average $\delta^{18}\text{O}$ from inner and converted outer shell layers; age 22 to 27.5 years = converted outer shell (Fig. 4d).

$\delta^{18}\text{O}$ -SST equations are commonly used to reconstruct palaeo-SST from the measured $\delta^{18}\text{O}_{\text{Shell}}$ values. Although several $\delta^{18}\text{O}$ -SST relationships have been developed specifically for *Tridacna*, they differ in calibration datasets, $\delta^{18}\text{O}_{\text{Seawater}}$ scale treatment and normalisation procedures (Wang et al., 2022). Therefore, in this study, we adopted the $\delta^{18}\text{O}$ -SST equation proposed by Morissette et al. (2023), where a generalised relationship was derived based on a compilation of data from marine molluscs, expressed as follows:

$$\delta^{18}\text{O}_{\text{Carbonate, VPDB}} - \delta^{18}\text{O}_{\text{Water, VSMOW}} = -0.21 \times T (^{\circ}\text{C}) + 4.05 \quad (3)$$

which can be converted to:

$$\text{SST } (^{\circ}\text{C}) = -4.76 \times (\delta^{18}\text{O}_{\text{Shell, VPDB}} - \delta^{18}\text{O}_{\text{Seawater, VSMOW}}) + 19.14 \quad (4)$$

where $\delta^{18}\text{O}_{\text{Shell}}$ represents the measured stable oxygen isotope composition of the shell, reported relative to the VPDB scale, and $\delta^{18}\text{O}_{\text{Seawater}}$ denotes the stable oxygen isotope composition of the surrounding seawater, reported relative to the VSMOW scale.

Neither previous $\delta^{18}\text{O}_{\text{Seawater}}$ records nor continuous modern *in situ* $\delta^{18}\text{O}_{\text{Seawater}}$ observations are available for the study site; therefore, $\delta^{18}\text{O}_{\text{Seawater}}$ values were estimated from SSS. Previous studies have shown that local SSS usually has a linear relationship with local $\delta^{18}\text{O}_{\text{Seawater}}$ (Arias-Ruiz et al., 2017; Ayling et al., 2015; Wang et al., 2022; Watanabe and Oba, 1999; Yamanashi et al., 2016; Yan et al.,

2013). We used the salinity- $\delta^{18}\text{O}_{\text{Seawater}}$ relationship developed for the Tropical Pacific by LeGrande and Schmidt (2006):

$$\delta^{18}\text{O}_{\text{Seawater}} (\text{‰}, \text{VSMOW}) = 0.27 \times \text{SSS} - 8.88 \quad (5)$$

where the mean daily SSS monitored from the Lizard Island Research Station from 2012 to 2015 was 35.00 ppt. Direct measurements of past $\delta^{18}\text{O}_{\text{Seawater}}$ are not available for fossil or archaeological shell records, and estimating $\delta^{18}\text{O}_{\text{Seawater}}$ from modern observational data or salinity- $\delta^{18}\text{O}_{\text{Seawater}}$ relationships is therefore a common and necessary approach in $\delta^{18}\text{O}$ -based palaeo-SST reconstructions. We therefore used the modern SSS-derived $\delta^{18}\text{O}_{\text{Seawater}}$ value of 0.57 ‰ VSMOW to produce a constant-SSS reference reconstruction, rather than treating it as an absolute constraint on LIA seawater composition. To evaluate the effect of this assumption, we also performed a monthly SSS-corrected sensitivity reconstruction using modern monthly SSS observations from Jiigurru. In this sensitivity test, monthly $\delta^{18}\text{O}_{\text{Seawater}}$ values were calculated from monthly SSS using the LeGrande and Schmidt (2006) relationship and were then applied to the $\delta^{18}\text{O}$ -SST equation. Full calculations are provided in Supplementary Table S2.

The reconstructed monthly palaeo-SST varies between 22.5 and 30.4 °C (mean = 25.8 °C) and exhibits smooth variations from summer to winter (Fig. 4e). Mean SST in summer (December to February) is 27.6 °C, whilst mean SST in winter (June to August) is 24.3 °C. In the monthly SSS-corrected sensitivity reconstruction, the correction changes reconstructed SST by approximately -0.47 to +0.70 °C relative to the constant-SSS reconstruction, with an annual mean offset of +0.27 °C. The resulting mean annual SST is approximately 26.1 °C. Mean summer SST increases from 27.6 °C to approximately 27.9 °C, and mean winter SST increases from 24.3 °C to approximately 24.7 °C.

4.4. $\delta^{13}\text{C}_{\text{Shell}}$ composition and precipitation-related hydroclimatic variability

Previous studies have shown that *Tridacna* $\delta^{13}\text{C}_{\text{Shell}}$ can be influenced by the $\delta^{13}\text{C}$ of dissolved inorganic carbon (DIC), ontogenetic effects and physiological controls (Elliot et al., 2009; Jones et al., 1986; Owen et al., 2008). Comparison of the inner and outer shell records from specimen 21GC indicates that ontogenetic effects are relatively weak overall, although a slight increase in $\delta^{13}\text{C}_{\text{Outer shell}}$ values with age is evident (Fig. 6d). This trend is substantially smaller than those reported for some modern *Tridacna* records, which show progressively more positive $\delta^{13}\text{C}_{\text{Shell}}$ values through ontogeny (Elliot et al., 2009; Jones et al., 1986; Romanek et al., 1987).

Absolute values of $\delta^{13}\text{C}$ between the inner and outer shell layers did differ, with the outer shell on average offset by +1.4 ‰ relative to the inner shell layer (Fig. 5a). The wavelet analysis indicated that the values of $\delta^{13}\text{C}_{\text{Outer shell}}$ showed clear seasonal oscillations (Fig. 5b) that were not present in the inner shell layer (Fig. 5c). This implies that the drivers of $\delta^{13}\text{C}_{\text{Shell}}$ composition in the inner and outer shell layers may differ, with $\delta^{13}\text{C}_{\text{Inner shell}}$ composition determined by layer-specific vital or physiological effects (Jones et al., 1986).

Previous studies have reported a positive correlation between $\delta^{18}\text{O}_{\text{Outer shell}}$ and $\delta^{13}\text{C}_{\text{Outer shell}}$ (Elliot et al., 2009; Killam et al., 2020; Romanek et al., 1987; Watanabe et al., 2004). However, this relationship is not universal, as some *Tridacna* records do not show this pattern (Aharon, 1983). A comparison of the $\delta^{18}\text{O}_{\text{Outer shell}}$ and $\delta^{13}\text{C}_{\text{Outer shell}}$ profiles in this study reveals similar positive temporal trends, albeit with a consistent one-month offset between the peaks and troughs of their seasonal cycles (Fig. 6a). The $\delta^{18}\text{O}_{\text{Shell}}$ troughs occurred from reconstructed December to February (summer), whereas the peaks occurred from June to August (winter). In contrast, for $\delta^{13}\text{C}_{\text{Shell}}$ (x-axis in reverse order), the troughs occurred from January to March, whereas peaks occurred from July to September (one month offset from $\delta^{18}\text{O}_{\text{Shell}}$) (Fig. 6a). This offset corresponds with the offset between modern temperature and precipitation instrumental records, where highest summer

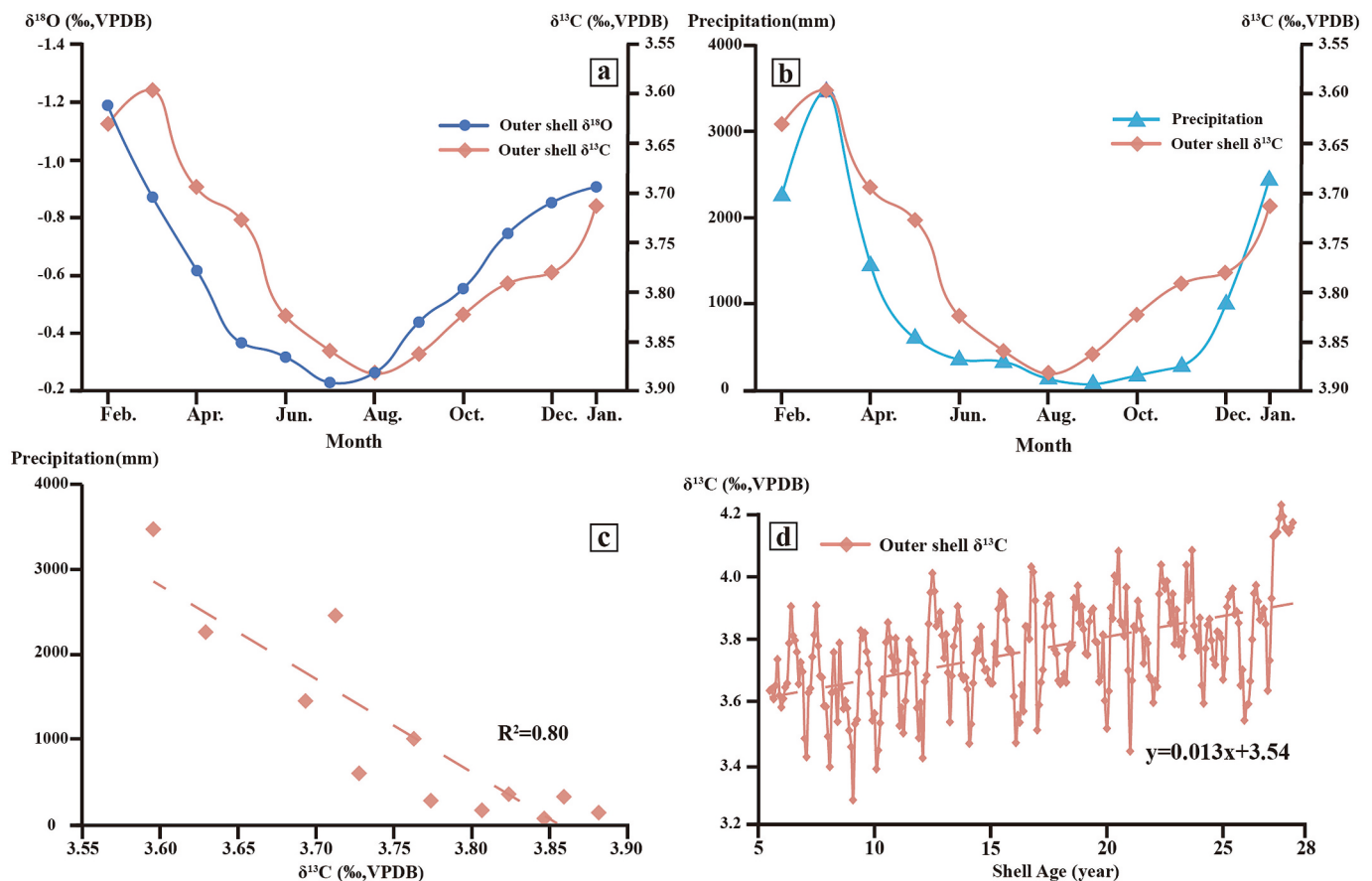


Fig. 6. $\delta^{13}\text{C}$ data of the shell. (a) Average monthly $\delta^{18}\text{O}$ (blue line with circles) and $\delta^{13}\text{C}$ (orange line and diamonds) isotope signals of the outer shell of the studied giant clam. (b) Average monthly modern instrumental precipitation (light blue line with triangles) and $\delta^{13}\text{C}$ (orange line and diamonds) isotope signals. (c) Linear regression between the average monthly modern instrumental precipitation and $\delta^{13}\text{C}$ ratios, with $R^2 = 0.80$. (d) Outer shell $\delta^{13}\text{C}$ ratios with a slightly ontogenetic increase trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperatures occur from December to February, whereas the wettest months occurred between January and March.

Further comparison indicates that the monthly instrumental precipitation record exhibits a pattern similar to that of the monthly averaged $\delta^{13}\text{C}_{\text{Outer shell}}$ values (Fig. 6b). Specifically, the wet season corresponds to lower $\delta^{13}\text{C}_{\text{Outer shell}}$ values from late summer to autumn, whereas the dry season is associated with higher $\delta^{13}\text{C}_{\text{Outer shell}}$ values from late winter to spring. The 12 monthly climatological means show an inverse relationship between instrumental precipitation and $\delta^{13}\text{C}_{\text{Outer shell}}$ ($R^2 = 0.80$, $n = 12$) (Fig. 6c). This correspondence supports an association with precipitation-related seasonality, but the regression compares two averaged seasonal cycles rather than repeated paired observations through time and is based on only 12 monthly values. It therefore supports a qualitative interpretation but is insufficient for quantitative precipitation calibration or for attributing shell $\delta^{13}\text{C}$ variability solely to precipitation.

At Jigurr, no groundwater or anthropogenic input contributes DIC to the seawater, aside from terrestrial runoff, which is controlled by precipitation. Vegetated catchments can supply isotopically light terrestrial carbon to nearshore waters during runoff events (Bouillon et al., 2011; Gillikin et al., 2006; Mook and Vogel, 1968). Increased runoff and terrigenous input may also reduce light availability and primary productivity, limiting biological modification of the local DIC pool (Mills et al., 2025). Consequently, for the outer shell layer of the *Tridacna* in this study, more negative $\delta^{13}\text{C}_{\text{Shell}}$ values may partly reflect greater precipitation-related freshwater and terrestrial DIC influence, consistent with previous studies (Arias-Ruiz et al., 2017; Duprey et al., 2014; McConnaughey et al., 1997; McConnaughey and Gillikin, 2008;

Mook and Vogel, 1968; Owen et al., 2008).

However, carbon isotopes exhibit complex behaviour due to biological vital effects, hydrological processes, and additional factors that limit their use for quantitative precipitation reconstruction. First, ontogenetically related vital effects associated with shell growth are expressed as a slight increase in $\delta^{13}\text{C}_{\text{Outer shell}}$ values with shell age (Fig. 6d). Although this trend could be readily removed using statistical linear detrending methods, it remains unclear whether the ontogenetic trend is uniform throughout the entire lifespan of the shell or whether its magnitude varies among different *Tridacna* species. Second, the relationship between $\delta^{13}\text{C}_{\text{Shell}}$ and precipitation is also modulated by local hydrological cycles and the surrounding terrestrial environment. In particular, the presence of persistent surface runoff can alter the DIC composition in water bodies, thereby influencing how well $\delta^{13}\text{C}_{\text{Shell}}$ records reflect direct precipitation inputs. Thus, hydrological mixing, terrestrial carbon inputs and ecosystem metabolism must be considered when interpreting $\delta^{13}\text{C}_{\text{Shell}}$ -rainfall relationships, particularly in river-influenced coastal and reef-lagoon settings (Gillikin et al., 2007; McConnaughey and Gillikin, 2008). Third, the palaeoenvironmental records in the *Tridacna* shell may be influenced by the Suess effect (Duprey et al., 2014). The outer shell $\delta^{13}\text{C}$ values of 21GC are approximately 0.7 ‰ higher than those of a modern *T. gigas* outer shell from the southern GBR (Elliot et al., 2009), consistent with the Suess effect, whereby the release of ^{13}C -depleted carbon from fossil fuel combustion since the Industrial Revolution has lowered the $\delta^{13}\text{C}$ of the atmosphere, oceanic DIC, and subsequently modern shell carbonate (Böhm et al., 1996; Butler et al., 2010; Druffel and Benavides, 1986; Druffel and Griffin, 1999; Duprey et al., 2014; Revelle and Suess, 1957; Swart

et al., 2010).

Overall, this study demonstrates that $\delta^{13}\text{C}_{\text{shell}}$ values in the outer shell layer of *Tridacna* exhibit clear seasonal variability linked to precipitation-related hydroclimatic processes. This pattern supports the interpretation of the record as a qualitative indicator of seasonal hydroclimatic variability. However, the influence of ontogenetic effects, local hydrology, and the Suess effect introduces uncertainties that currently limit its use for quantitative precipitation reconstruction.

4.5. The reconstructed environment at the end of LIA in the GBR

Modern *in situ* instrumental records from Jigurrurru indicate a mean annual SST of 26.7 °C for 1995–2015. Under the constant-SSS reference reconstruction, the mean annual SST reconstructed from shell $\delta^{18}\text{O}$ during the late LIA was 25.8 °C, approximately 0.9 °C lower than the modern instrumental mean. Summer SSTs were approximately 1.2 °C cooler than modern values, whereas winter SSTs were similar to present-day conditions. However, the monthly SSS-corrected sensitivity reconstruction increases the reconstructed mean annual SST to approximately 26.1 °C, reducing the inferred annual cooling to approximately 0.6 °C. The inferred summer cooling is similarly reduced from approximately 1.2 °C to approximately 0.9 °C (Fig. 7). These results indicate that the absolute magnitude of cooling is sensitive to the assumed SSS and $\delta^{18}\text{O}_{\text{seawater}}$ baseline, although cooler annual and summer conditions remain evident under both reconstructions. The $\delta^{13}\text{C}_{\text{outer shell}}$ record is interpreted here as a qualitative indicator of precipitation-related hydroclimatic variability rather than as a quantitative precipitation reconstruction. The clearer and more pronounced seasonal $\delta^{13}\text{C}_{\text{outer shell}}$ variations observed in shell 21GC, compared to modern specimens from the southern GBR (Elliot et al., 2009), imply stronger precipitation-related seasonality during the late Little Ice Age. However, differences between specimens and sites limit the extent to which this contrast can be interpreted as a quantitative difference in precipitation between regions. Based on the *Tridacna* proxy evidence, we suggest that late LIA cooling, widely observed in Northern Hemisphere records, was also expressed in the northern GBR and may represent a regional Southern Hemisphere expression of this broader climatic transition. During the period represented by shell 21GC, the northern GBR appears to have experienced cooler annual and summer SSTs than during the modern instrumental period, while qualitatively the $\delta^{13}\text{C}_{\text{outer shell}}$ record implies more pronounced precipitation-related hydroclimatic seasonality relative to modern shell records.

ENSO is the most significant interannual climate mode affecting the

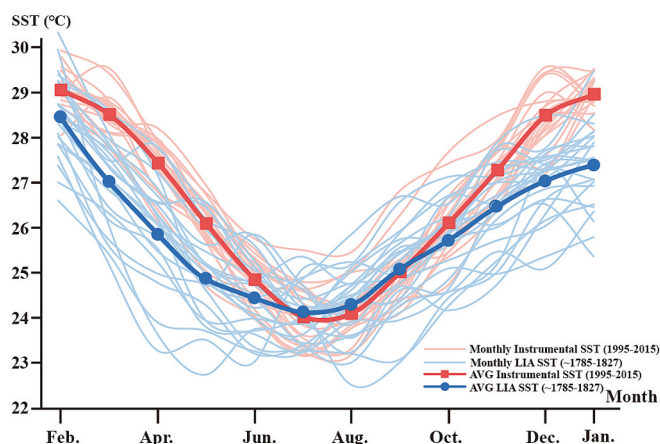


Fig. 7. LIA SST reconstructed from the shell of a giant clam (blue lines) and modern instrumental records of SST between 1995 and 2015 (red lines) (Australian Institute of Marine Science, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tropical Pacific, with events typically recurring every 2 to 7 years (Philander, 1990). ENSO variability plays a crucial role in the lives, economies, and migration patterns of communities across the Pacific (Wang et al., 2017). For instance, research conducted in the Coral Sea has shown that ENSO events influenced Lapita colonisation efforts in previously unexplored areas of Remote Oceania (Anderson et al., 2006; Duprey et al., 2014). We found that reconstructed patterns in annual average SST featured oscillations characterized by a seesaw pattern. Spectral analysis using the Multi-Taper Method (MTM) identified local spectral maxima at approximately 2.60, 2.37 and 2.13 years within the broader 2–3-year band, with the first two exceeding the 95% confidence level and the third exceeding the 90% confidence level (Fig. 8). This concentration of spectral power within the 2–3-year band is likely to represent local ENSO-like variability, as similar interannual cycles have been recognised in *Tridacna* shells by earlier studies (Anderson et al., 2006; Ayling et al., 2015; Driscoll et al., 2014; Liu et al., 2019; Welsh et al., 2011; Zhou et al., 2022). Compared with the canonical 2–7 year periodicity of modern ENSO, the pronounced 2–3 year cycle in shell 21GC suggests relatively high-frequency ENSO-like variability in the northern GBR during the terminal phase of the LIA.

In the GBR, warm SST anomalies with reduced rainfall are associated with El Niño events, whereas cooler SST anomalies with increased rainfall are influenced by La Niña events (Wang et al., 2017). We applied the adapted ONI criteria to the reconstructed northern GBR SST anomalies (Fig. 9a) and identified 10 local ENSO-like events using the ± 0.5 °C threshold, comprising 5 El Niño-like and 5 La Niña-like events (Fig. 9b). Using the stronger 1σ criterion, we identified no strong El Niño-like events but three strong La Niña-like events at shell ages 13, 19 and 21, corresponding approximately to the early 1800s (Fig. 9c). This event frequency provides a useful basis for comparison with other high-resolution tropical Pacific marine records that quantify ENSO variability using similar 30- or 31-year windows.

Our reconstruction of local ENSO-like events from shell 21GC indicates that El Niño-like events were more frequent toward the end of the 1700s, whereas La Niña-like events became more prevalent, both in frequency and strength, during the early 1800s. This pattern differs from the modern ENSO asymmetry, in which El Niño events often exhibit stronger SST anomalies than La Niña events (An and Jin, 2004; Burgers and Stephenson, 1999; Khider et al., 2011). A similar tendency toward enhanced late eighteenth- to early nineteenth-century ENSO variability has been reported from South Pacific coral archives (Druffel et al., 2015).

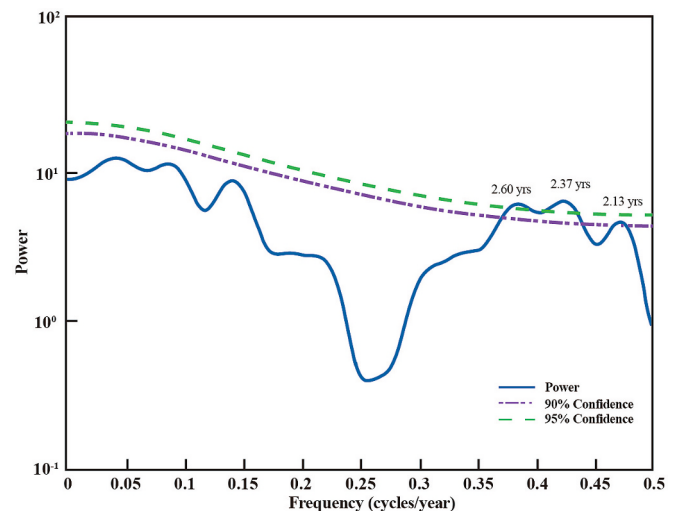


Fig. 8. Spectral analysis using the Multi-taper Method (MTM) reveals local maxima at approximately 2.60, 2.37, and 2.13 years within the 2–3-year band, with the first two exceeding the 95% confidence level and the third exceeding the 90% confidence level.

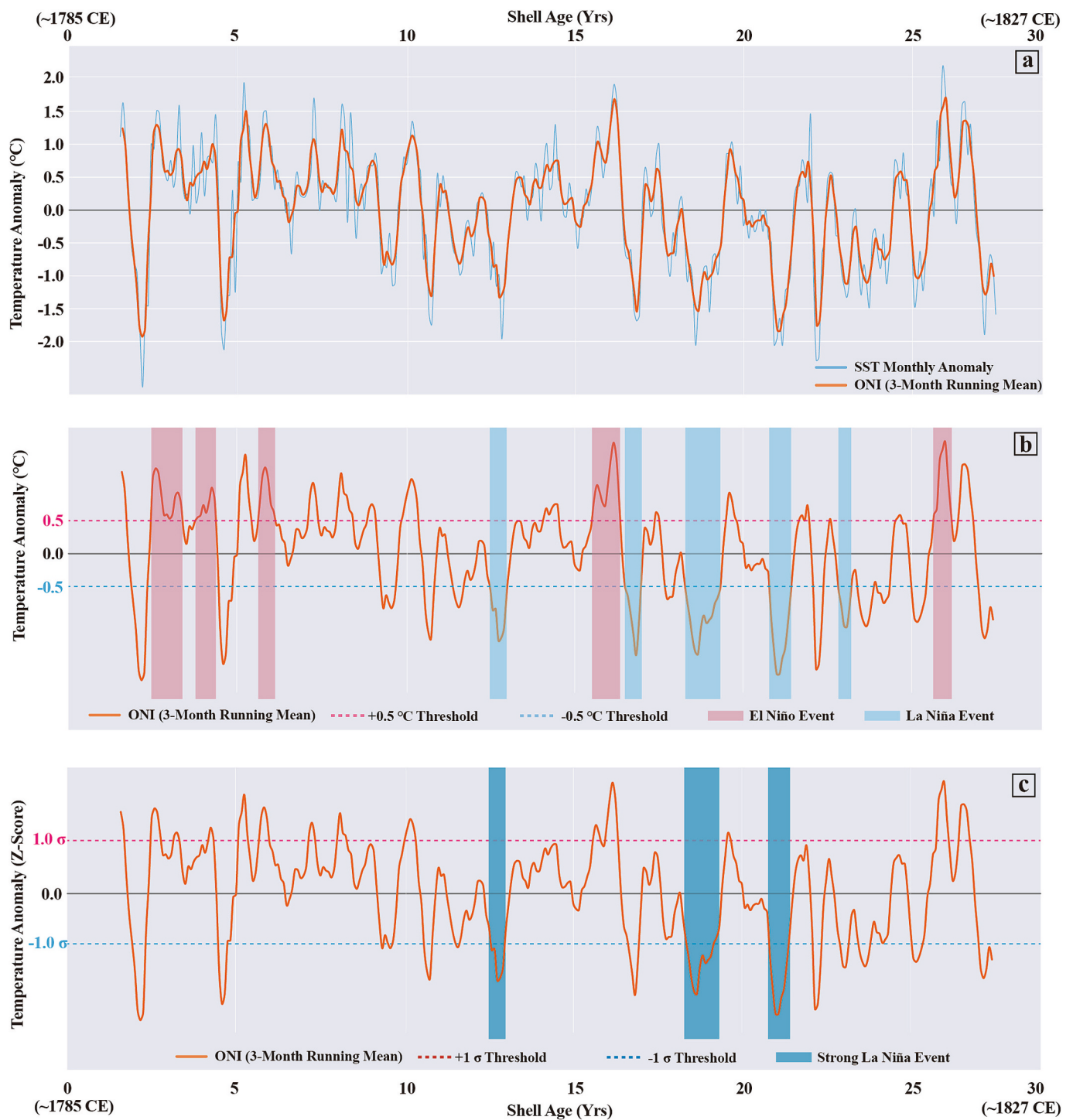


Fig. 9. Identification of local ENSO-like events from reconstructed northern GBR SST anomalies using criteria adapted from the standard Niño-3.4 ONI framework. (a) Monthly reconstructed SST anomaly (blue line) and 3-month moving average SST anomaly (red line). (b) ONI with ± 0.5 °C threshold standard and a persistence criterion of at least 5 consecutive overlapping seasons, including NDJ months. The potential local El Niño and La Niña events are marked with pink frames and blue frames. (c) ONI with an adapted 1σ z-score threshold standard and a persistence criterion of at least 5 consecutive overlapping seasons, including NDJ months. The strong local La Niña events are marked with blue frames. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The 10 ENSO-like events identified in the ~30-year 21GC record provide a basis for comparison with other tropical Pacific archives that report ENSO event frequencies over similar multi-decadal windows. The Palmyra fossil coral $\delta^{18}\text{O}$ records provide a central equatorial Pacific benchmark for last-millennium ENSO variability (Cobb et al., 2003). Their monthly resolved coral records cover five time windows, 928–961

CE, 1149–1220, 1317–1464, 1635–1703 and 1886–1998, and their sliding 30-year event counts vary from intervals with very weak ENSO activity to intervals with approximately 5 to 6 El Niño or La Niña events per 30 years. Although the main LIA Palmyra window predates shell 21GC, the 5 El Niño-like and 5 La Niña-like events identified in 21GC fall within the upper range of phase-specific event frequencies reported from

Palmyra. This suggests that the high-frequency ENSO-like variability recorded by 21GC is not anomalous when viewed against tropical Pacific coral benchmarks, although direct event-by-event comparison is not possible because of the age and location differences.

Western Pacific marginal records provide useful comparison for evaluating ENSO event frequencies in ENSO-sensitive reef archives. Han et al. (2020) reconstructed ENSO variability from a northern South China Sea coral $\delta^{18}\text{O}$ record spanning 1851–2007 CE and identified 34 El Niño and 31 La Niña events, including 5 El Niño and 3 La Niña events before the widespread instrumental period around 1870. Their sliding 31-year analysis showed relatively high ENSO event counts before ~1900, approximately 6–8 events, and slightly lower counts after ~1930, approximately 5–7 events. Jiang et al. (2021) similarly used Xisha Islands Porites coral Sr/Ca-SST anomalies and 31-year windows to quantify ENSO variability, showing intensified ENSO variability and increased El Niño frequency during the late Medieval Climate Anomaly. Although they are not direct analogues for shell 21GC because of differences in age, hemisphere, proxy system, and hydrographic setting, they demonstrate that western Pacific marginal reef archives can record substantial changes in ENSO event frequency over multi-decadal windows. The 10 local ENSO-like events identified in the ~30-year 21GC record therefore fall within a plausible range for ENSO-sensitive tropical Pacific reef archives.

The irregularity in ENSO-like pacing and the shift toward stronger La Niña-like conditions in the early 1800s may have been influenced by external forcings, including volcanic activity. The early nineteenth century coincided with the Dalton Minimum and several major volcanic events, including the unidentified tropical 1808/1809 eruption and the 1815 Tambora eruption (Timmreck et al., 2021). Tambora was located on Sumbawa Island, Indonesia, within the Maritime Continent and close to the Indo-Pacific warm-pool region (Raible et al., 2016). Large tropical volcanic eruptions can inject sulfate aerosols into the stratosphere, reduce incoming shortwave radiation, and produce rapid surface cooling, which can perturb tropical Pacific SST gradients, trade winds and ENSO dynamics (Predybaylo et al., 2020; Raible et al., 2016). Proxy-based ENSO reconstructions also suggest a tendency toward more La Niña-like conditions several years after major volcanic events (Dätwyler et al., 2019). The stronger negative SST anomalies and La Niña-like events recorded in shell 21GC during the early 1800s may therefore partly reflect enhanced solar-volcanic forcing during this interval. However, the volcanic signal is not clearly separable from internal ENSO variability in the shell record. Although the calibrated median ages place shell 21GC approximately between 1785 and 1827 CE, each radiocarbon measurement has an analytical uncertainty of ± 25 ^{14}C yr and regional ΔR correction has an uncertainty of ± 56 ^{14}C yr. These uncertainties mean that individual shell anomalies cannot be assigned precise calendar years and therefore cannot be confidently aligned with either the 1808/1809 eruption or the 1815 Tambora eruption. We therefore interpret volcanic forcing as a plausible contributing influence rather than a direct causal explanation.

The comparison indicates that the 2–3 year pacing and high event frequency observed in shell 21GC are broadly consistent with the range of variability recorded by central and western Pacific coral archives. However, because these records differ in age, hemisphere, proxy sensitivity and hydrographic setting, we do not interpret the La Niña-like dominance in 21GC as definitive evidence for basin-wide reorganisation of the Pacific Walker Circulation. Instead, we interpret it as a local-to-regional Southern Hemisphere response of the northern GBR to ENSO-sensitive tropical Pacific variability.

4.6. Southern Hemisphere context for late LIA variability

The 21GC record provides a high-resolution 30-year environmental window from the northern GBR during the terminal phase of the Little Ice Age. A central question is whether the cooler SSTs, stronger precipitation-related seasonality and early nineteenth-century La Niña-

like conditions reconstructed from Jiigurru reflect broader patterns of Southern Hemisphere climate variability during this interval. To address this, we compare the 21GC record with independent proxy archives from the Southern Hemisphere, including marine, ice-core, speleothem and lacustrine records.

The cooler annual and summer SSTs reconstructed from 21GC are consistent with broader evidence for late LIA cooling in the Southern Hemisphere. Multi-proxy reconstructions from Australasia indicate cooler conditions during parts of the last millennium, with a pronounced regional expression during the seventeenth to early nineteenth centuries (Gergis et al., 2016; Neukom et al., 2014; PAGES 2k Consortium, 2019). Marine records from the Australian region provide particularly relevant support. Coral records from the GBR and northwest Australia indicate cooler SSTs and/or hydrographic changes during the LIA, consistent with changes in Indo-Pacific ocean-atmosphere circulation rather than a purely local Jiigurru signal (Hendy et al., 2002; Zinke et al., 2015). Antarctic ice-core and glacier records also document late-millennium cooling and circulation changes, showing that LIA cooling was not restricted to Northern Hemisphere archives (Orsi et al., 2012; Simms et al., 2021).

The magnitude of cooling inferred from 21GC also appears consistent with the broader hemispheric contrast between Northern and Southern Hemisphere climate responses. Under the constant-SSS reference reconstruction, 21GC indicates an annual cooling of approximately 0.9 °C, with summer cooling of approximately 1.2 °C; the monthly SSS-corrected sensitivity reconstruction reduces these estimates to approximately 0.6 °C and 0.9 °C, respectively. These values are generally smaller than, or at the lower end of, many Northern Hemisphere LIA cooling estimates of approximately 1.0–1.5 °C (Baum, 2019; Divine et al., 2011; Ge et al., 2010; Ljungqvist et al., 2012; Munn, 2002; PAGES 2k Consortium, 2019; Tierney et al., 2015). This pattern is consistent with evidence that industrial-era warming first emerged in tropical oceans and Northern Hemisphere continental regions, while Southern Hemisphere warming lagged by several decades (Abram et al., 2016; IPCC et al., 2023). The smaller and delayed Southern Hemisphere response has been linked to the larger oceanic surface area, greater heat capacity, and delayed heat uptake by the Southern Ocean (Armour et al., 2016; Marshall and Speer, 2012). Therefore, the 21GC record is consistent with both regional late LIA cooling in the northern GBR and the broader pattern of a more muted Southern Hemisphere temperature response compared with the Northern Hemisphere.

The La Niña-like conditions inferred from 21GC during the early nineteenth century are also supported by other Southern Hemisphere and tropical Pacific margin records. Galápagos coral $\delta^{18}\text{O}$ records from the eastern tropical Pacific indicate prolonged cooling and enhanced upwelling during the early 1800s, consistent with La Niña-like oceanographic conditions (Druffel et al., 2015). Speleothem records from northern Peru have been interpreted as recording increased precipitation and a La Niña-like hydroclimatic response during the nineteenth century (Reuter et al., 2009). In southeastern Australia, lake records indicate wetter conditions and expanded lake levels during the early nineteenth century, providing further evidence for hydroclimatic changes consistent with stronger La Niña influence in parts of the Southern Hemisphere (Barr et al., 2014; Gergis et al., 2012). Historical ENSO reconstructions also suggest that La Niña conditions were unusually frequent during parts of the nineteenth century, although the strongest expression occurs later than the lifespan of shell 21GC (Gergis and Fowler, 2009).

Terrestrial records from southeastern Australia provide additional evidence that the late LIA involved coupled changes in temperature, moisture balance and atmospheric circulation. Speleothem and lake-sediment archives document shifts in effective moisture, vegetation, fire activity and Southern Ocean or westerly influences during the LIA interval (Dixon et al., 2017; McGowan et al., 2018; Tibby et al., 2017). Although these archives are not direct analogues for a marine shell record from the northern GBR, they show that Southern Hemisphere

climate variability during the late LIA was expressed through linked temperature, hydroclimatic and circulation changes.

Taken together, these comparisons place the site-specific 21GC reconstruction within a broader Southern Hemisphere palaeoclimate context. The cooler SSTs, more pronounced seasonal hydroclimatic variability in $\delta^{13}\text{C}_{\text{Outer shell}}$ and early nineteenth-century La Niña-like conditions recorded by the shell are broadly consistent with independent evidence from other Southern Hemisphere archives. However, the comparison also shows that the late LIA was not expressed as a uniform hemispheric signal. Instead, Southern Hemisphere records point to regionally variable but broadly connected responses involving tropical Pacific variability, ENSO teleconnections, Southern Ocean influence and hydroclimatic reorganisation. We therefore interpret 21GC as a site-specific high-resolution marine record that captures a regional Southern Hemisphere expression of terminal LIA climate variability, rather than as a standalone reconstruction or a spatially representative baseline for the entire northern GBR.

5. Conclusions

Sclerochronology and sclerochemistry proxies derived from a *Tridacna* shell in this study offer a 30-year-long high-resolution snapshot of seasonal-scale palaeoenvironmental variability during the pre-industrial period in the Southern Hemisphere. This reinforces the significant potential of *Tridacna* shell proxies to provide high-resolution palaeoenvironmental and palaeo-ENSO records, enabling further detailed investigations into palaeoenvironmental changes and their interactions with human activity in tropical and subtropical regions.

We compared stable isotope records ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) from both the inner and outer shell layers and showed that the $\delta^{18}\text{O}$ values of the inner shell layer had a consistent negative offset of 0.21 ‰ relative to the outer shell layer. The removal of this offset enabled us to combine records from both shell layers and reconstruct a longer and more continuous $\delta^{18}\text{O}_{\text{Shell}}$ record. Under a constant modern SSS-derived $\delta^{18}\text{O}_{\text{Seawater}}$ baseline, reconstructed SSTs ranged from 22.5 to 30.4 °C, with a mean annual SST of 25.8 °C. A monthly SSS-corrected sensitivity reconstruction reduced the inferred annual cooling relative to the modern instrumental period from approximately 0.9 °C to approximately 0.6 °C, while both approaches consistently indicate cooler annual and summer SSTs during the late LIA. These results demonstrate that the magnitude of cooling is sensitive to the assumed SSS and $\delta^{18}\text{O}_{\text{Seawater}}$ baseline, but the overall cooling signal is robust across reconstruction methods. The $\delta^{13}\text{C}_{\text{Outer shell}}$ record indicates more pronounced precipitation-related seasonal hydroclimatic variability, but should be interpreted as a qualitative hydroclimatic indicator rather than a quantitative precipitation reconstruction.

The environment reconstructed from the shell provides site-specific evidence that late LIA cooling was also expressed in the northern GBR. The cooling inferred from this tropical Southern Hemisphere site appears smaller in magnitude than many Northern Hemisphere reconstructions, although the absolute temperature offset remains conditional on the assumed SSS and $\delta^{18}\text{O}_{\text{Seawater}}$ baseline. The record also reveals pronounced local ENSO-like variability on 2–3-year time-scales, with stronger La Niña-like conditions during the early nineteenth century. Comparison with tropical Pacific and Southern Hemisphere proxy records suggests that these site-specific patterns are consistent with broader regional climate variability during the terminal LIA.

These records provide improved insight into ENSO dynamics and broader climatic variability during the terminal phase of the Little Ice Age and prior to the onset of modern global warming. However, comparisons with regional palaeoenvironmental reconstructions reveal pronounced spatial heterogeneity as well as differences among archive types. Consequently, we advocate for more detailed, locally focused sub-annual palaeoenvironmental reconstructions from a range of regions and proxy archives in the Southern Hemisphere in future studies. In particular, seasonally resolved sclerochronological archives offer strong

potential for capturing past ENSO-related oceanographic variability. Records from climatically sensitive reef environments, not limited to the Great Barrier Reef and the Coral Sea, but extending across the broader South Pacific, could provide robust chronologies and geochemical proxies sensitive to SST and precipitation-related hydroclimatic variability, thereby enabling detailed reconstructions of interannual to decadal ENSO variability during this climatically transitional interval.

CRedit authorship contribution statement

Bohao Dong: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amy L. Prendergast:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Sean Ulm:** Writing – review & editing, Funding acquisition. **Kotaro Shirai:** Writing – review & editing, Data curation. **Russell N. Drysdale:** Writing – review & editing, Methodology. **Ian J. McNiven:** Writing – review & editing. **Vladimir Levchenko:** Writing – review & editing, Methodology. **Henri Wong:** Writing – review & editing. **Mark Meekan:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that have or could be perceived to have influenced the work reported in this article.

Acknowledgements

This research was supported by the Australian Research Council Centre of Excellence for Australian Biodiversity and Heritage (CE170100015). BD was supported by the Melbourne Research Scholarship from the University of Melbourne and a Postgraduate Research Award (PGRA) (ALNSTU12820) from the Australian Institute of Nuclear Science and Engineering (AINSE) Ltd. AP was supported by an Australian Research Council DECRA Fellowship (DE200100890). KS was supported by JSPS KAKENHI Grant Number JP19KK0352. We acknowledge the financial support for the Centre for Accelerator Science (CAS), at ANSTO, through the Australian National Collaborative Research Infrastructure Strategy (NCRIS). We are grateful to CAS chemistry laboratory staff and Chris Vardanega (ANSTO) for their assistance with the AMS carbon dating and other analysis. We appreciate Dr. Ling Chung and the Trace Analysis for Chemical, Earth and Environmental Science (TrACEES) platform at the University of Melbourne for the assistance with sample preparation and optical microscope analysis. We acknowledge the Dinggaal and Ngurrungu Aboriginal communities as partners in this research. The authors appreciate the anonymous reviewers for their constructive suggestions and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2026.105717>.

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

References

- Abram, N.J., McGregor, H.V., Tierney, J.E., Evans, M.N., McKay, N.P., Kaufman, D.S., 2016. Early onset of industrial-era warming across the oceans and continents. *Nature* 536, 411–418. <https://doi.org/10.1038/nature19082>.
- Aharon, P., 1983. 140,000-yr isotope climatic record from raised coral reefs in New Guinea. *Nature* 304, 720–723. <https://doi.org/10.1038/304720a0>.

- Aharon, P., 1991. Recorders of reef environment histories: stable isotopes in corals, giant clams, and calcareous algae. *Coral Reefs* 10, 71–90. <https://doi.org/10.1007/BF00571826>.
- Aharon, P., Chappell, J., 1983. Carbon and oxygen isotope probes of reef environment histories. *Perspect. Coral Reefs* 1–15.
- Aharon, P., Chappell, J., 1986. Oxygen isotopes, sea level changes and the temperature history of a coral reef environment in New Guinea over the last 105 years. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 56, 337–379. [https://doi.org/10.1016/0031-0182\(86\)90101-X](https://doi.org/10.1016/0031-0182(86)90101-X).
- Alidoostsalimi, M., Prendergast, A.L., Ulm, S., Drysdale, R.N., Brown, J., Klaebe, R.M., Dong, B., 2025. Sclerochronology and oxygen isotope variations in modern *Conomurex luhuanus* shells: an archive for reconstructing palaeotemperature and shellfish gathering on the Great Barrier Reef, Australia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 659, 112633. <https://doi.org/10.1016/j.palaeo.2024.112633>.
- Alidoostsalimi, M., Prendergast, A.L., Ulm, S., McNiven, I.J., Lambrides, A.B.J., Drysdale, R.N., Brown, J., Kneppers, M.C., Klaebe, R.M., Collins, S.J., Corporation, N.I., Corporation, W.A., 2026. Reconstructing seasonally focused shellfish harvesting strategies of first nations communities on the northern Great Barrier Reef (Australia) during the late Holocene. *J. Archaeol. Res.* <https://doi.org/10.21203/rs.3.rs-8846183/v1>.
- An, S.-I., Jin, F.-F., 2004. Nonlinearity and asymmetry of ENSO*. *J. Clim.* 17, 2399–2412. [https://doi.org/10.1175/1520-0442\(2004\)017%3C2399:NAOE%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017%3C2399:NAOE%3E2.0.CO;2).
- Anderson, A., Chappell, J., Gagan, M., Grove, R., 2006. Prehistoric maritime migration in the Pacific islands: an hypothesis of ENSO forcing. *The Holocene* 16, 1–6. <https://doi.org/10.1191/0959683606hl901ft>.
- Arias-Ruiz, C., Elliot, M., Bézou, A., Pedoja, K., Husson, L., Cahyarini, S.Y., Cariou, E., Michel, E., La, C., Manssouri, F., 2017. Geochemical fingerprints of climate variation and the extreme La Niña 2010–11 as recorded in a *Tridacna squamosa* shell from Sulawesi, Indonesia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 487, 216–228. <https://doi.org/10.1016/j.palaeo.2017.08.037>.
- Armour, K.C., Marshall, J., Scott, J.R., Donohoe, A., Newsom, E.R., 2016. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nat. Geosci.* 9, 549–554. <https://doi.org/10.1038/ngeo2731>.
- Arndt, I., Coenen, D., Evans, D., Renema, W., Müller, W., 2023. Quantifying sub-seasonal growth rate changes in fossil giant clams using wavelet transformation of daily Mg/Ca cycles. *Geochim. Geophys. Res.* 24, e2023GC010992. <https://doi.org/10.1029/2023GC010992>.
- Aubert, A., Lazareth, C.E., Cabioch, G., Boucher, H., Yamada, T., Iryu, Y., Farman, R., 2009. The tropical giant clam *Hippopus hippopus* shell, a new archive of environmental conditions as revealed by sclerochronological and $\delta^{18}\text{O}$ profiles. *Coral Reefs* 28, 989–998. <https://doi.org/10.1007/s00338-009-0538-0>.
- Australian Institute of Marine Science, 2017. Northern Australia Automated Marine Weather And Oceanographic Stations. <https://doi.org/10.25845/5C09BF93F315D>.
- Ayling, B.F., Chappell, J., Gagan, M.K., McCulloch, M.T., 2015. ENSO variability during MIS 11 (424–374 ka) from *Tridacna gigas* at Huon Peninsula, Papua New Guinea. *Earth Planet. Sci. Lett.* 431, 236–246. <https://doi.org/10.1016/j.epsl.2015.09.037>.
- Bajnai, D., Fiebig, J., Tomašových, A., Milner Garcia, S., Rollier-Bard, C., Raddatz, J., Höfler, N., Primo-Ramos, C., Brand, U., 2018. Assessing kinetic fractionation in brachiopod calcite using clumped isotopes. *Sci. Rep.* 8, 533. <https://doi.org/10.1038/s41598-017-17353-7>.
- Barr, C., Tibby, J., Gell, P., Tyler, J., Zawadzki, A., Jacobsen, G.E., 2014. Climate variability in south-eastern Australia over the last 1500 years inferred from the high-resolution diatom records of two crater lakes. *Quat. Sci. Rev.* 95, 115–131. <https://doi.org/10.1016/j.quascirev.2014.05.001>.
- Batenbury, S.J., Reichert, G.J., Jilbert, T., Janse, M., Wesselingh, F.P., Renema, W., 2011. Interannual climate variability in the Miocene: high resolution trace element and stable isotope ratios in giant clams. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 306, 75–81. <https://doi.org/10.1016/j.palaeo.2011.03.031>.
- Baum, R.M., 2019. Taking the Earth's temperature: 200 years of research has established why the Earth is as warm as it is and how burning fossil fuels is making it warmer. *Substantia*. <https://doi.org/10.13128/SUBSTANTIA-264>, 27–42 Pages.
- Böhme, F., Joachimski, M.M., Lehnert, H., Morgenroth, G., Kretschmer, W., Vacelet, J., Dullo, W.-Chr., 1996. Carbon isotope records from extant Caribbean and South Pacific sponges: evolution of $\delta^{13}\text{C}$ in surface water DIC. *Earth Planet. Sci. Lett.* 139, 291–303. [https://doi.org/10.1016/0012-821X\(96\)00006-4](https://doi.org/10.1016/0012-821X(96)00006-4).
- Bouillon, S., Connolly, R.M., Gillikin, D.P., 2011. Use of stable isotopes to understand food webs and ecosystem functioning in estuaries. In: *Treatise on Estuarine and Coastal Science*. Elsevier, pp. 143–173. <https://doi.org/10.1016/B978-0-12-374711-2.00711-7>.
- Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360. <https://doi.org/10.1017/S0033822200033865>.
- Burgers, G., Stephenson, D.B., 1999. The “normality” of El Niño. *Geophys. Res. Lett.* 26, 1027–1030. <https://doi.org/10.1029/1999GL900161>.
- Butler, P.G., Schöne, B.R., 2017. New research in the methods and applications of sclerochronology. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 465, 295–299. <https://doi.org/10.1016/j.palaeo.2016.11.013>.
- Butler, P.G., Richardson, C.A., Scourse, J.D., Wanamaker, A.D., Shammon, T.M., Bennell, J.D., 2010. Marine climate in the Irish Sea: analysis of a 489-year marine master chronology derived from growth increments in the shell of the clam *Arctica islandica*. *Quat. Sci. Rev.* 29, 1614–1632. <https://doi.org/10.1016/j.quascirev.2009.07.010>.
- Cobb, K.M., Charles, C.D., Cheng, H., Edwards, R.L., 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature* 424, 271–276. <https://doi.org/10.1038/nature01779>.
- Dätwyler, C., Abram, N.J., Grosjean, M., Wahl, E.R., Neukom, R., 2019. El Niño–Southern Oscillation variability, teleconnection changes and responses to large volcanic eruptions since AD 1000. *Int. J. Climatol.* 39, 2711–2724. <https://doi.org/10.1002/joc.5983>.
- Divine, D., Isaksson, E., Martma, T., Meijer, H.A.J., Moore, J., Pohjola, V., Van De Wal, R. S.W., Godtliessen, F., 2011. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. *Polar Res.* 30, 7379. <https://doi.org/10.3402/polar.v30i0.7379>.
- Dixon, B.C., Tyler, J.J., Lorrey, A.M., Goodwin, I.D., Gergis, J., Drysdale, R.N., 2017. Low-resolution Australasian palaeoclimate records of the last 2000 years. *Clim. Past* 13, 1403–1433. <https://doi.org/10.5194/cp-13-1403-2017>.
- Dong, B., Hausmann, N., Otter, L.M., Drysdale, R.N., Prendergast, A.L., 2025a. Visualising and quantifying Mg/Ca and Sr/Ca heterogeneity in the isochronous growth increments of bivalve shells (*Tridacna*). *Chem. Geol.* 696, 123109. <https://doi.org/10.1016/j.chemgeo.2025.123109>.
- Dong, B., Kumar, R., Shirai, K., Drysdale, R.N., Prendergast, A.L., 2025b. Advances in giant clam (*Tridacnidae* spp.) sclerochronology and sclerochemistry. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 661, 112576. <https://doi.org/10.1016/j.palaeo.2024.112576>.
- Driscoll, R., Elliot, M., Russon, T., Welsh, K., Yokoyama, Y., Tudhope, A., 2014. ENSO reconstructions over the past 60 ka using giant clams (*Tridacna* sp.) from Papua New Guinea. *Geophys. Res. Lett.* 41, 6819–6825. <https://doi.org/10.1002/2014GL061446>.
- Druffel, E.R.M., Benavides, L.M., 1986. Input of excess CO₂ to the surface ocean based on $^{13}\text{C}/^{12}\text{C}$ ratios in a banded Jamaican sclerosponge. *Nature* 321, 58–61. <https://doi.org/10.1038/321058a0>.
- Druffel, E.R.M., Griffin, S., 1999. Variability of surface ocean radiocarbon and stable isotopes in the southwestern Pacific. *J. Geophys. Res. Oceans* 104, 23607–23613. <https://doi.org/10.1029/1999JC900212>.
- Druffel, E.R.M., Griffin, S., Vetter, D., Dunbar, R.B., Mucciarone, D.M., 2015. Identification of frequent La Niña events during the early 1800s in the east equatorial Pacific. *Geophys. Res. Lett.* 42, 1512–1519. <https://doi.org/10.1002/2014GL062997>.
- Duprey, N., Lazareth, C.E., Corrège, T., Le Cornec, F., Maes, C., Pujol, N., Madeng-Yogo, M., Caquineau, S., Soares Derome, C., Cabioch, G., 2012. Early mid-Holocene SST variability and surface-ocean water balance in the southwest Pacific. *Paleoceanography* 27, 2012PA002350. <https://doi.org/10.1029/2012PA002350>.
- Duprey, N., Galipaud, J.C., Cabioch, G., Lazareth, C.E., 2014. Isotopic records from archeological giant clams reveal a variable climate during the southwestern Pacific colonization ca. 3.0ka BP. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 404, 97–108. <https://doi.org/10.1016/j.palaeo.2014.04.002>.
- Duprey, N., Lazareth, C.E., Dupouy, C., Butscher, J., Farman, R., Maes, C., Cabioch, G., 2015. Calibration of seawater temperature and $\delta^{18}\text{O}$ seawater signals in *Tridacna maxima*'s $\delta^{18}\text{O}$ shell record based on in situ data. *Coral Reefs* 34, 437–450. <https://doi.org/10.1007/s00338-014-1245-z>.
- Elliot, M., Welsh, K., Chilcott, C., McCulloch, M., Chappell, J., Ayling, B., 2009. Profiles of trace elements and stable isotopes derived from giant long-lived *Tridacna gigas* bivalves: potential applications in paleoclimate studies. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 280, 132–142. <https://doi.org/10.1016/j.palaeo.2009.06.007>.
- Fousiya, A.A., Alberti, M., Achyuthan, H., Chakraborty, S., Watanabe, T.K., Gandhi, N., Reddy, A.P., Lone, A.M., 2022. Anomalous $\delta^{18}\text{O}$ signal in a giant clam shell (*Tridacna maxima*) from the Lakshadweep Archipelago, India: signature of thermal stress during a coral bleaching event. *Coral Reefs* 41, 1173–1185. <https://doi.org/10.1007/s00338-022-02263-6>.
- Fousiya, A.A., Malik, J.N., Paul, D., Chakraborty, S., Achyuthan, H., 2024. Microstructure and growth rate variability in a giant clam (*Tridacna maxima*) from the Lakshadweep Archipelago, India: implications for their use as biological monitors to trace extreme weather events. *Coral Reefs* 43, 319–332. <https://doi.org/10.1007/s00338-023-02455-8>.
- Gannon, M.E., Pérez-Huerta, A., Aharon, P., Street, S.C., 2017. A biomineralization study of the Indo-Pacific giant clam *Tridacna gigas*. *Coral Reefs* 36, 503–517. <https://doi.org/10.1007/s00338-016-1538-5>.
- Ge, Q.-S., Zheng, J.-Y., Hao, Z.-X., Shao, X.-M., Wang, W., Luterbacher, J., 2010. Temperature variation through 2000 years in China: an uncertainty analysis of reconstruction and regional difference. *Geophys. Res. Lett.* 37, 2009GL041281. <https://doi.org/10.1029/2009GL041281>.
- Gergis, J., Gallant, A.J.E., Braganza, K., Karoly, D.J., Allen, K., Cullen, L., D'Arrigo, R., Goodwin, I., Grierson, P., McGregor, S., 2012. On the long-term context of the 1997–2009 ‘Big Dry’ in South-Eastern Australia: insights from a 206-year multi-proxy rainfall reconstruction. *Clim. Chang.* 111, 923–944. <https://doi.org/10.1007/s10584-011-0263-x>.
- Gergis, J., Neukom, R., Gallant, A.J.E., Karoly, D.J., 2016. Australasian temperature reconstructions spanning the Last Millennium. *J. Clim.* 29, 5365–5392. <https://doi.org/10.1175/JCLI-D-13-00781.1>.
- Gergis, J.L., Fowler, A.M., 2009. A history of ENSO events since a.D. 1525: implications for future climate change. *Clim. Chang.* 92, 343–387. <https://doi.org/10.1007/s10584-008-9476-z>.
- Gillikin, D.P., Lorrain, A., Bouillon, S., Willenz, P., Dehairs, F., 2006. Stable carbon isotopic composition of *Mytilus edulis* shells: relation to metabolism, salinity, $\delta^{13}\text{C}$ DIC and phytoplankton. *Org. Geochem.* 37, 1371–1382. <https://doi.org/10.1016/j.orggeochem.2006.03.008>.
- Gillikin, D.P., Lorrain, A., Meng, L., Dehairs, F., 2007. A large metabolic carbon contribution to the $\delta^{13}\text{C}$ record in marine aragonitic bivalve shells. *Geochim. Cosmochim. Acta* 71, 2936–2946. <https://doi.org/10.1016/j.gca.2007.04.003>.
- Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. *Paleontol. Electron.* 4.

- Han, T., Yu, K., Yan, Hong, Jiang, W., Yan, Hongqiang, Tao, S., 2020. Coral $\delta^{18}\text{O}$ -based reconstruction of El Niño-Southern Oscillation from the northern south China sea since 1851 AD. *Quat. Int.* 550, 159–168. <https://doi.org/10.1016/j.quaint.2020.04.032>.
- Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N., Bronk Ramsey, C., Grootes, P.M., Hughen, K.A., Kromer, B., Reimer, P.J., Adkins, J., Burke, A., Cook, M.S., Olsen, J., Skinner, L.C., 2020. Marine20 - the marine radiocarbon age calibration curve (0-55,000 cal BP). *Radiocarbon* 62, 779–820. <https://doi.org/10.1017/RDC.2020.68>.
- Hendy, E.J., Gagan, M.K., Alibert, C.A., McCulloch, M.T., Lough, J.M., Isdale, P.J., 2002. Abrupt decrease in Tropical Pacific Sea surface salinity at end of Little Ice Age. *Science* 295, 1511–1514. <https://doi.org/10.1126/science.1067693>.
- Hori, M., Sano, Y., Ishida, A., Takahata, N., Shirai, K., Watanabe, T., 2015. Middle Holocene daily light cycle reconstructed from the strontium/calcium ratios of a fossil giant clam shell. *Sci. Rep.* 5, 8734. <https://doi.org/10.1038/srep08734>.
- Hu, Y., Sun, X., Cheng, H., Yan, H., 2020. Evidence from giant-clam $\delta^{18}\text{O}$ of intense El Niño-Southern Oscillation-related variability but reduced frequency 3700 years ago. *Clim. Past* 16, 597–610. <https://doi.org/10.5194/cp-16-597-2020>.
- IPCC, Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorpe, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W.L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E.L., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Sahan, Y., Sokona, Y., Sörensson, A.A., Tignor, M., van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewhin, B., van der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J.J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ürgé-Vorsatz, D., Xiao, C., Yassaa, N., Romero, J., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Birt, A., Ha, M., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestedt, J.S., Hansen, G., Ludden, C., Masson-Delmotte, V., Matthews, J.B.R., Mintenbeck, K., Pirani, A., Poloczanska, E., Leprince-Ringuet, N., Péan, C., 2023. In: Core Writing Team, Lee, H., Romero, J., IPCC (Eds.), IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland. <https://doi.org/10.59327/IPCC/AR6-9789291691647>.
- Jiang, L., Yu, K., Tao, S., Wang, S., Han, T., Jiang, W., 2021. ENSO variability during the medieval climate anomaly as recorded by *Porites* Corals from the Northern South China Sea. *Paleoceanogr. Paleoclimatol.* 36, e2020PA004173. <https://doi.org/10.1029/2020PA004173>.
- Johnson, A.L.A., Valentine, A.M., Schöne, B.R., Leng, M.J., Goolaerts, S., 2022. Sclerochronological evidence of pronounced seasonality from the late Pliocene of the southern North Sea basin and its implications. *Clim. Past* 18, 1203–1229. <https://doi.org/10.5194/cp-18-1203-2022>.
- Jones, D.S., Williams, D.F., Romanek, C.S., 1986. Life history of symbiont-bearing giant clams from stable isotope profiles. *Science* 231, 46–48. <https://doi.org/10.1126/science.231.4733.46>.
- Khider, D., Stott, L.D., Emile-Geay, J., Thunell, R., Hammond, D.E., 2011. Assessing El Niño Southern Oscillation variability during the past millennium. *Paleoceanography* 26, 2011PA002139. <https://doi.org/10.1029/2011PA002139>.
- Killam, D., Thomas, R., Al-Najjar, T., Clapham, M., 2020. Interspecific and intrashell stable isotope variation among the Red Sea giant clams. *Geochim. Geophys. Geosyst.* 21. <https://doi.org/10.1029/2019GC008669>.
- Kneppers, M.C., Lambrides, A.B.J., Litster, M., Ulm, S., McNiven, I.J., Harris, M., MacLaurin, C., Nguurumungu Indigenous Corporation, Walmbaar Aboriginal Corporation RNTBC, 2024. Beyond hinges and spires: a critical examination of archaeomalacological quantification methodologies using coral reef molluscan assemblages from Jiigurru (Lizard Island Group), northern Great Barrier Reef. *Aust. Archaeol.* 90, 299–318. <https://doi.org/10.1080/03122417.2024.2402586>.
- Komagoe, T., Watanabe, T., Shirai, K., Yamazaki, A., Uematu, M., 2018. Geochemical and microstructural signals in giant clam *Tridacna maxima* recorded typhoon events at Okinotori Island, Japan. *J. Geophys. Res. Biogeosci.* 123, 1460–1474. <https://doi.org/10.1029/2017JG004082>.
- Kotov, S., Pálíke, H., 2018. QAnalyzeSeries – a cross-platform time series tuning and analysis tool (other). *Geology*. <https://doi.org/10.1002/essar.10500226.1>.
- Lambrides, A.B.J., McNiven, I.J., Aird, S.J., Lowe, K.A., Moss, P., Rowe, C., Harris, C., MacLaurin, C., Slater, S.A., Carroll, K., Cedar, M.H., Petchey, F., Reepmeyer, C., Harris, M., Charlie, J., McGreen, E., Baru, P., Ulm, S., 2020. Changing use of Lizard Island over the past 4000 years and implications for understanding Indigenous offshore island use on the Great Barrier Reef. *Qld. Archaeol. Res.* 23, 43–109. <https://doi.org/10.25120/qar.23.2020.3778>.
- LeGrande, A.N., Schmidt, G.A., 2006. Global gridded data set of the oxygen isotopic composition in seawater. *Geophys. Res. Lett.* 33, L12604. <https://doi.org/10.1029/2006GL026011>.
- Letulle, T., Gaspard, D., Daéron, M., Arnaud-Godet, F., Vinçon-Laugier, A., Suan, G., Lécuyer, C., 2023. Multi-Proxy Assessment of Brachiopod Shell Calcite as a Potential Archive of Seawater Temperature and Oxygen Isotope Composition.
- Li, M., Hinnov, L., Kump, L., 2019. Acycle: time-series analysis software for paleoclimate research and education. *Comput. Geosci.* 127, 12–22. <https://doi.org/10.1016/j.cageo.2019.02.011>.
- Liu, C., Yan, H., Fei, H., Ma, X., Zhang, W., Shi, G., Soon, W., Dodson, J., An, Z., 2019. Temperature seasonality and ENSO variability in the northern South China Sea during the medieval climate anomaly interval derived from the Sr/Ca ratios of *Tridacna* shell. *J. Asian Earth Sci.* 180, 103880. <https://doi.org/10.1016/j.jseas.2019.103880>.
- Ljungqvist, F.C., Krusic, P.J., Brattström, G., Sundqvist, H.S., 2012. Northern Hemisphere temperature patterns in the last 12 centuries. *Clim. Past* 8, 227–249. <https://doi.org/10.5194/cp-8-227-2012>.
- Ma, X., Yan, H., Fei, H., Liu, C., Shi, G., Huang, E., Wang, Y., Qu, X., Lian, E., Dang, H., 2020. A high-resolution $\delta^{18}\text{O}$ record of modern *Tridacna* gigas bivalve and its paleoenvironmental implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 554, 109800. <https://doi.org/10.1016/j.palaeo.2020.109800>.
- Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779–787. <https://doi.org/10.1038/33859>.
- Marshall, J., Speer, K., 2012. Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nat. Geosci.* 5, 171–180. <https://doi.org/10.1038/ngeo1391>.
- McConaughy, T.A., Gillikin, D.P., 2008. Carbon isotopes in mollusk shell carbonates. *Geo-Mar. Lett.* 28, 287–299. <https://doi.org/10.1007/s00367-008-0116-4>.
- McConaughy, T.A., Burdett, J., Whelan, J.F., Paull, C.K., 1997. Carbon isotopes in biological carbonates: Respiration and photosynthesis. *Geochim. Cosmochim. Acta* 61, 611–622. [https://doi.org/10.1016/S0016-7037\(96\)00361-4](https://doi.org/10.1016/S0016-7037(96)00361-4).
- McGowan, H., Callow, J.N., Soderholm, J., McGrath, G., Campbell, M., Zhao, J., 2018. Global warming in the context of 2000 years of Australian alpine temperature and snow cover. *Sci. Rep.* 8, 4394. <https://doi.org/10.1038/s41598-018-22766-z>.
- Mei, Y.J., Shao, D., Wang, Y.H., Yang, Z.K., Yang, W.Q., Gao, Y.S., He, S.M., Zheng, Y., Li, A.G., Sun, L.G., 2018. Measurement of Sr/Ca ratio in *Tridacna* spp. shells from South China Sea: a comparison of SR-XRF and ICP-OES analysis methods. *Spectrosc. Spectr. Anal.* 38, 1640–1647.
- Mies, M., Scozzafave, M.S., Braga, F., Sumida, P.Y.G., 2017. Giant clams. In: *Marine Ornamental Species Aquaculture*. Wiley, pp. 510–535. <https://doi.org/10.1002/9781119169147.ch23a>.
- Mills, K., Sosdian, S., Muir, D.D., John, E.H., Santodomingo, N., Johnson, K., Buse, B., Waheed, Z., 2025. Crystallographic and geochemical responses of giant clams on turbid reefs. *Sci. Rep.* 15, 7365. <https://doi.org/10.1038/s41598-025-90614-y>.
- Mook, W.G., Vogel, J.C., 1968. Isotopic equilibrium between shells and their environment. *Science* 159, 874–875.
- Morissette, O., Trueman, C.N., Sturrock, A.M., Geffen, A.J., Shirai, K., 2023. Limited evidence for species-specific sensitivity of temperature-dependent fractionation of oxygen stable isotope in biominerals: a meta-analysis. *Methods Ecol. Evol.* 14, 1719–1731. <https://doi.org/10.1111/2041-210X.14122>.
- Munn, R.E. (Ed.), 2002. *Encyclopedia of Global Environmental Change*. Wiley, Chichester; New York.
- Neukom, R., Gergis, J., Karoly, D.J., Wanner, H., Curran, M., Elbert, J., González-Rouco, F., Linsley, B.K., Moy, A.D., Mundo, I., Raible, C.C., Steig, E.J., Van Ommen, T., Vance, T., Villalba, R., Zinke, J., Frank, D., 2014. Inter-hemispheric temperature variability over the past millennium. *Nat. Clim. Chang.* 4, 362–367. <https://doi.org/10.1038/nclimate2174>.
- Orsi, A.J., Cornuelle, B.D., Severinghaus, J.P., 2012. Little Ice Age cold interval in West Antarctica: evidence from borehole temperature at the West Antarctic Ice Sheet (WAIS) divide. *Geophys. Res. Lett.* 39, 2012GL051260. <https://doi.org/10.1029/2012GL051260>.
- Oschmann, W., 2009. Sclerochronology: Editorial. *Int. J. Earth Sci.* 98, 1–2. <https://doi.org/10.1007/s00531-008-0403-3>.
- Othman, A.S.B., Goh, G.H.S., Todd, P.A., 2010. The distribution and status of giant clams (family Tridacnidae) - a short review. *Raffles Bull. Zool.* 58, 103–111.
- Owen, E.F., Wanamaker, A.D., Feindel, S.C., Schöne, B.R., Rawson, P.D., 2008. Stable carbon and oxygen isotope fractionation in bivalve (*Placopecten magellanicus*) larval aragonite. *Geochim. Cosmochim. Acta* 72, 4687–4698. <https://doi.org/10.1016/j.gca.2008.06.029>.
- PAGES 2k Consortium, 2019. Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. *Nat. Geosci.* 12, 643–649. <https://doi.org/10.1038/s41561-019-0400-0>.
- PAGES 2k Consortium, Emile-Geay, J., McKay, N.P., Kaufman, D.S., Von Gunten, L., Wang, J., Anchukaitis, K.J., Abram, N.J., Addison, J.A., Curran, M.A.J., Evans, M.N., Henley, B.J., Hao, Z., Martrat, B., McGregor, H.V., Neukom, R., Pederson, G.T., Stenni, B., Thirumalai, K., Werner, J.P., Xu, C., Divine, D.V., Dixon, B.C., Gergis, J., Mundo, I.A., Nakatsuka, T., Phipps, S.J., Routson, C.C., Steig, E.J., Tierney, J.E., Tyler, J.J., Allen, K.J., Bertler, N.A.N., Björklund, J., Chase, B.M., Chen, M.-T., Cook, E., De Jong, R., DeLong, K.L., Dixon, D.A., Ekaykin, A.A., Ersek, V., Filipsson, H.L., Francus, P., Freund, M.B., Frezzotti, M., Gaire, N.P., Gajewski, K., Ge, Q., Gooose, H., Gornostaeva, A., Grosjean, M., Horiuchi, K., Hormes, A., Husum, K., Isaksson, E., Kandasamy, S., Kawamura, K., Kilbourne, K.H., Koç, N., Leduc, G., Linderholm, H.W., Lorrey, A.M., Mikhalenko, V., Mortyn, P.G., Motoyama, H., Moy, A.D., Mulvaney, R., Munz, P.M., Nash, D.J., Oerter, H., Opel, T., Orsi, A.J., Ovhinnikov, D.V., Porter, T.J., Roop, H.A., Saenger, C., Sano, M., Sauchyn, D., Saunders, K.M., Seidenkrantz, M.-S., Severi, M., Shao, X., Sicre, M.-A., Sigl, M., Sinclair, K., St. George, S., St. Jacques, J.-M., Thamban, M., Kuwar Thapa, U., Thomas, E.R., Turney, C., Uemura, R., Viau, A.E., Vladimirova, D.O., Wahl, E.R., White, J.W.C., Yu, Z., Zinke, J., 2017. A global multiproxy database for temperature reconstructions of the Common Era. *Sci. Data* 4, 170088. <https://doi.org/10.1038/sdata.2017.88>.

- Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh Program performs time-series analysis. *EOS Trans. Am. Geophys. Union* 77, 379. <https://doi.org/10.1029/96EO00259>.
- Peardha, M., Schöne, B.R., Black, B.A., Corrège, T., 2021. Advances of sclerochronology research in the last decade. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 570. <https://doi.org/10.1016/j.palaeo.2021.110371>.
- Philander, S.G., 1990. El Niño, La Niña, and the Southern Oscillation. *Geol. Mag.* 127, 478. <https://doi.org/10.1017/S0016756800015351>.
- Predybaylo, E., Stenchikov, G., Wittenberg, A.T., Osipov, S., 2020. El Niño/Southern Oscillation response to low-latitude volcanic eruptions depends on ocean pre-conditions and eruption timing. *Commun. Earth Environ.* 1, 12. <https://doi.org/10.1038/s43247-020-0013-y>.
- Prendergast, A.L., Pryor, A.J.E., Reade, H., Stevens, R.E., 2018. Seasonal records of palaeoenvironmental change and resource use from archaeological assemblages. *J. Archaeol. Sci. Rep.* 21, 1191–1197. <https://doi.org/10.1016/j.jasrep.2018.08.006>.
- Raible, C.C., Brönnimann, S., Auchmann, R., Brohan, P., Frölicher, T.L., Graf, H.-F., Jones, P., Luterbacher, J., Muthers, S., Neukom, R., Robock, A., Self, S., Sudrajat, A., Timmerck, C., Wegmann, M., 2016. Tambora 1815 as a test case for high impact volcanic eruptions: earth system effects. *Wiley Interdiscip. Rev. Clim. Chang.* 7, 569–589. <https://doi.org/10.1002/wcc.407>.
- Reuter, J., Stott, L., Khider, D., Sinha, A., Cheng, H., Edwards, R.L., 2009. A new perspective on the hydroclimate variability in northern South America during the Little Ice Age. *Geophys. Res. Lett.* 36, 2009GL041051. <https://doi.org/10.1029/2009GL041051>.
- Reuter, M., Spreter, P.M., Brachert, T.C., Mertz-Kraus, R., Wrozyna, C., 2022. Giant clam (Tridacna) distribution in the Gulf of Oman in relation to past and future climate. *Sci. Rep.* 12, 16506. <https://doi.org/10.1038/s41598-022-20843-y>.
- Revelle, R., Suess, H.E., 1957. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO₂ during the past decades. *Tellus* 9, 18–27. <https://doi.org/10.1111/j.2153-3490.1957.tb01849.x>.
- Richard, B., 1992. The Giant Clam: Hatchery and Nursery Culture Manual. Australian Centre for International Agricultural Research, Canberra, ACT.
- Romanek, C.S., Grossman, E.L., 1989. Stable isotope profiles of Tridacna maxima as environmental indicators. *PALAIOS* 4, 402. <https://doi.org/10.2307/3514585>.
- Romanek, C.S., Jones, D.S., Williams, D.F., Krantz, D.E., Radtke, R., 1987. Stable isotopic investigation of physiological and environmental changes recorded in shell carbonate from the giant clam Tridacna maxima. *Mar. Biol.* 94, 385–393. <https://doi.org/10.1007/BF00428244>.
- Rosewater, J., 1965. The Family Tridacnidae in the Indo-Pacific.
- Sano, Y., Kobayashi, S., Shirai, K., Takahata, N., Matsumoto, K., Watanabe, T., Sowa, K., Iwai, K., 2012. Past daily light cycle recorded in the strontium/calcium ratios of giant clam shells. *Nat. Commun.* 3. <https://doi.org/10.1038/ncomms1763>.
- Schöne, B.R., 2008. The curse of physiology - challenges and opportunities in the interpretation of geochemical data from mollusk shells. *Geo-Mar. Lett.* 28, 269–285. <https://doi.org/10.1007/s00367-008-0114-6>.
- Simms, A.R., Bentley, M.J., Simkins, L.M., Zurbuchen, J., Reynolds, L.C., DeWitt, R., Thomas, E.R., 2021. Evidence for a “Little Ice Age” glacial advance within the Antarctic Peninsula – examples from glacially-overrun raised beaches. *Quat. Sci. Rev.* 271, 107195. <https://doi.org/10.1016/j.quascirev.2021.107195>.
- Swart, P.K., Greer, L., Rosenheim, B.E., Moses, C.S., Waite, A.J., Winter, A., Dodge, R.E., Helmle, K., 2010. The ¹³C Suess effect in scleractinian corals mirror changes in the anthropogenic CO₂ inventory of the surface oceans. *Geophys. Res. Lett.* 37, 2009GL041397. <https://doi.org/10.1029/2009GL041397>.
- Tibby, J., Barr, C., Marshall, J.C., M C Gregor, G.B., Moss, P.T., Arnold, L.J., Page, T.J., Questiaux, D., Olley, J., Kemp, J., Spooner, N., Petherick, L., Penny, D., Mooney, S., Moss, E., 2017. Persistence of wetlands on North Stradbroke Island (south-east Queensland, Australia) during the last glacial cycle: implications for Quaternary science and biogeography. *J. Quat. Sci.* 32, 770–781. <https://doi.org/10.1002/jqs.2981>.
- Tierney, J.E., Abram, N.J., Anchukaitis, K.J., Evans, M.N., Giry, C., Kilbourne, K.H., Saenger, C.P., Wu, H.C., Zinke, J., 2015. Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. *Paleoceanography* 30, 226–252. <https://doi.org/10.1002/2014PA002717>.
- Timmerck, C., Toohey, M., Zanchettin, D., Brönnimann, S., Lundstad, E., Wilson, R., 2021. The unidentified eruption of 1809: a climatic cold case. *Clim. Past* 17, 1455–1482. <https://doi.org/10.5194/cp-17-1455-2021>.
- Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. *Bull. Am. Meteorol. Soc.* 79, 61–78. [https://doi.org/10.1175/1520-0477\(1998\)079%3C0061:APGTWA%3E2.0.CO;2](https://doi.org/10.1175/1520-0477(1998)079%3C0061:APGTWA%3E2.0.CO;2).
- Trofimova, T., Alexandroff, S.J., Mette, M.J., Tray, E., Butler, P.G., Campana, S.E., Harper, E.M., Johnson, A.L.A., Morrongiello, J.R., Peardha, M., Schöne, B.R., Andersson, C., Andrus, C.F.T., Black, B.A., Burchell, M., Carroll, M.L., DeLong, K.L., Gillanders, B.M., Gronkjaer, P., Killam, D., Prendergast, A.L., Reynolds, D.J., Scourse, J.D., Shirai, K., Thébaud, J., Trueman, C., de Winter, N., 2020. Fundamental questions and applications of sclerochronology: Community-defined research priorities. *Estuar. Coast. Shelf Sci.* 245. <https://doi.org/10.1016/j.eccs.2020.106977>.
- Ulm, S., McNiven, I.J., Aird, S.J., Lambrides, A.B.J., 2019. Sustainable harvesting of Conomurex luhuanus and Rochia nilotica by Indigenous Australians on the Great Barrier Reef over the past 2000 years. *J. Archaeol. Sci. Rep.* 28, 102017. <https://doi.org/10.1016/j.jasrep.2019.102017>.
- Ulm, S., McNiven, I.J., Summerhayes, G.R., Wu, P., Bunbury, M.M.E., Petchey, F., Hua, Q., Skelly, R., Lambrides, A.B.J., Rowe, C., Lowe, K.M., Reepmeyer, C.H., MacLaurin, C., Woo, K.G.P., Harris, M., Morgan, S.B., Turner-Kose, K.L., Slater, S.A., Connelly, J.D., Kneppers, M.C., Szabó, K., Fairbairn, A., Haberle, S.G., Hopf, F., Bultitude, R., Ash, J., Lewis, S.E., Beaman, R.J., Leon, J.X., McDowell, M.C., Potter, M., Connelly, B., Little, C., Jackson, S., McCarthy, J., Nothdurft, L.D., Zhao, J., Bird, M.I., Felgate, M.W., Cobus, B., 2024. Early Aboriginal pottery production and offshore island occupation on Jiigurru (Lizard Island group), Great Barrier Reef, Australia. *Quat. Sci. Rev.* 333, 108624. <https://doi.org/10.1016/j.quascirev.2024.108624>.
- Wanamaker, A.D., Kreutz, K.J., Schöne, B.R., Introne, D.S., 2011. Gulf of Maine shells reveal changes in seawater temperature seasonality during the Medieval Climate anomaly and the Little Ice Age. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 302, 43–51. <https://doi.org/10.1016/j.palaeo.2010.06.005>.
- Wang, C., Deser, C., Yu, J.-Y., DiNezio, P., Clement, A., 2017. El Niño and Southern Oscillation (ENSO): A Review. In: Glynn, P.W., Manziello, D.P., Enochs, I.C. (Eds.), *Coral Reefs of the Eastern Tropical Pacific, Coral Reefs of the World*. Springer Netherlands, Dordrecht, pp. 85–106. https://doi.org/10.1007/978-94-017-7499-4_4.
- Wang, G., Yan, H., Liu, C., Han, T., Zhou, P., Zhao, N., Wen, H., Fei, H., Dodson, J., 2022. Oxygen isotope temperature calibrations for modern Tridacna shells in western Pacific. *Coral Reefs* 41, 113–130. <https://doi.org/10.1007/s00338-021-02208-5>.
- Wang, Z., Gaetani, G., Liu, C., Cohen, A., 2013. Oxygen isotope fractionation between aragonite and seawater: developing a novel kinetic oxygen isotope fractionation model. *Geochim. Cosmochim. Acta* 117, 232–251. <https://doi.org/10.1016/j.gca.2013.04.025>.
- Warter, V., Müller, W., 2017. Daily growth and tidal rhythms in Miocene and modern giant clams revealed via ultra-high resolution LA-ICPMS analysis — a novel methodological approach towards improved sclerochemistry. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 465, 362–375. <https://doi.org/10.1016/j.palaeo.2016.03.019>.
- Warter, V., Müller, W., Wesselingh, F.P., Todd, J.A., Renema, W., 2015. Late Miocene seasonal to subdecadal climate variability in the Indo-west Pacific (East Kalimantan, Indonesia) preserved in giant clams. *Palaio* 30, 66–82. <https://doi.org/10.2110/palo.2013.061>.
- Watanabe, T., Oba, T., 1999. Daily reconstruction of water temperature from oxygen isotopic ratios of a modern Tridacna shell using a freezing microtome sampling technique. *J. Geophys. Res. Oceans* 104, 20667–20674. <https://doi.org/10.1029/1999jc900097>.
- Watanabe, T., Suzuki, A., Kawahata, H., Kan, H., Ogawa, S., 2004. A 60-year isotopic record from a mid-Holocene fossil giant clam (Tridacna gigas) in the Ryukyu Islands: physiological and paleoclimatic implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 212, 343–354. <https://doi.org/10.1016/j.palaeo.2004.07.001>.
- Watkins, J.M., Nielsen, L.C., Ryerson, F.J., DePaolo, D.J., 2013. The influence of kinetics on the oxygen isotope composition of calcium carbonate. *Earth Planet. Sci. Lett.* 375, 349–360. <https://doi.org/10.1016/j.epsl.2013.05.054>.
- Welsh, K., Elliot, M., Tudhope, A., Ayling, B., Chappell, J., 2011. Giant bivalves (Tridacna gigas) as recorders of ENSO variability. *Earth Planet. Sci. Lett.* 307, 266–270. <https://doi.org/10.1016/j.epsl.2011.05.032>.
- Yamanashi, J., Takayanagi, H., Isaji, A., Asami, R., Iryu, Y., 2016. Carbon and oxygen isotope records from tridacna derasa shells: toward establishing a reliable proxy for sea surface environments. *PLoS One* 11. <https://doi.org/10.1371/journal.pone.0157659>.
- Yan, H., 2020. Daily growth bands of giant clam shell: a potential paleoweather recorder. *Solid Earth Sci.* 5, 249–253. <https://doi.org/10.1016/j.sesci.2020.10.001>.
- Yan, H., Shao, D., Wang, Y., Sun, L., 2013. Sr/Ca profile of long-lived Tridacna gigas bivalves from South China Sea: a new high-resolution SST proxy. *Geochim. Cosmochim. Acta* 112, 52–65. <https://doi.org/10.1016/j.gca.2013.03.007>.
- Yan, H., Sun, L., Shao, D., Wang, Y., Wei, G., 2014. Higher sea surface temperature in the northern South China Sea during the natural warm periods of late Holocene than recent decades. *Chin. Sci. Bull.* 59, 4115–4122. <https://doi.org/10.1007/s11434-014-0317-3>.
- Yan, H., Sun, L., Shao, D., Wang, Y., 2015. Seawater temperature seasonality in the South China Sea during the late Holocene derived from high-resolution Sr/Ca ratios of Tridacna gigas. *Quat. Res. U. S.* 83, 298–306. <https://doi.org/10.1016/j.yqres.2014.12.001>.
- Yan, H., Liu, C., An, Z., Yang, W., Yang, Yuanjian, Huang, P., Qiu, S., Zhou, P., Zhao, N., Fei, H., Ma, X., Shi, G., Dodson, J., Hao, J., Yu, K., Wei, G., Yang, Yanan, Jin, Z., Zhou, W., 2020. Extreme weather events recorded by daily to hourly resolution biogeochemical proxies of marine giant clam shells. *Proc. Natl. Acad. Sci. USA* 117, 7038–7043. <https://doi.org/10.1073/pnas.1916784117>.
- Zhao, N., Yan, H., Luo, F., Yang, Y., Liu, S., Zhou, P., Liu, C., Dodson, J., 2023. Daily growth rate variation in Tridacna shells as a record of tropical cyclones in the South China Sea: Palaeoecological implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 615, 111444. <https://doi.org/10.1016/j.palaeo.2023.111444>.
- Zhou, P., Yan, H., Han, T., Liu, C., Yang, H., Luo, F., Liu, S., Wang, Z., Shen, X., Shi, G., Dodson, J., Zhou, W., 2022. Mid to late Holocene ENSO variability reconstructed by high-resolution Tridacna Sr/Ca records from the northern part of the South China Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 601, 111117. <https://doi.org/10.1016/j.palaeo.2022.111117>.
- Zinke, J., Hoell, A., Lough, J.M., Feng, M., Kuret, A.J., Clarke, H., Ricca, V., Rankenburg, K., McCulloch, M.T., 2015. Coral record of southeast Indian Ocean marine heatwaves with intensified Western Pacific temperature gradient. *Nat. Commun.* 6, 8562. <https://doi.org/10.1038/ncomms9562>.