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Penultimate glacial sea surface temperature and hydrologic variability in the tropical South Pacific from 150 ka Tahiti corals

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Abstract. Constraining climate models under extreme boundary conditions of the past on societally-relevant timescales is complicated by a common lack of high-resolution reconstructions of sea surface environmental variability for glacial periods. Here, we present subseasonally-resolved Sr/Ca and oxygen isotope ($\delta^{18}O$) records from well-preserved and precisely-dated fossil corals of the penultimate glacial and last glacial periods drilled by Integrated Ocean Drilling Program Expedition 310 "Tahiti Sea Level" in the central tropical South Pacific. The proxy records document the mean and seasonality of sea surface temperature (SST) and seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) at 153 ka and 148 ka, during Marine Isotope Stage (MIS) 6b, and around 30 ka during MIS 3a. Results show mean SST 2.8–4.0 °C lower than present for MIS 6b, and about 3.8 °C lower for MIS 3a. The MIS 6b SST differences are greater during the austral winter (3.7–4.4 °C lower) than during the austral summer (2.0–3.7 °C lower), indicating a greater SST seasonality relative to today during the penultimate glacial. A reconstructed higher mean $\delta^{18}O_{sw}$ for both MIS 6b and MIS 3a (+0.41‰ to +0.51‰ relative to today) suggest more saline surface waters in the central tropical South Pacific over the entire year. Our coral-based reconstructions of SST and hydrology may indicate a reduced mixed layer depth around Tahiti during the penultimate glacial and last glacial. A potential explanation is a westward-expanded South Pacific subtropical dry area relative to today, probably accompanied by lower activity and/or displacement of the South Pacific Convergence Zone.

1 Introduction

Ocean-atmosphere interactions in the tropical Pacific Ocean play a substantial role in global climate on seasonal and interannual timescales. The Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), areas of enhanced precipitation, are prominent features in the tropical-to-subtropical Pacific (Trenberth, 1976). Their activity and

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position change on seasonal and interannual timescales, partly related to the Western Pacific Warm Pool (WPWP) and the El Niño/Southern Oscillation (ENSO) (Vincent, 1994; Gouriou and Delcroix, 2002; Vincent et al., 2011). Knowledge of past ocean-atmosphere variability from geological archives is crucial for better understanding the natural range of Earth's climate system on these societally-relevant timescales. Especially, high-resolution sea surface temperature (SST) reconstructions for extreme climate conditions of the past (e.g., glacial periods) are essential to constrain numerical model simulations of past and future climate. However, widely-distributed foraminiferal Mg/Ca and alkenone records from deep-sea sediments commonly document long-term variability of millennial to multimillennial seawater temperature changes for depths of <50–100 m, due to low sedimentation rates and bioturbation in the open ocean. This precludes seasonal reconstructions of past ocean-atmosphere variability. Furthermore, rare glacial temperature reconstructions from marine sediments in the tropical-to-subtropical South Pacific result in large uncertainties and inconsistencies with climate model simulations (CLIMAP Project Members, 1976; MARGO Project Members, 2009; Tierney et al., 2020; Kageyama et al., 2021).

Corals are the most excellent archive for providing accurately dated high-resolution time series of ocean conditions near the sea surface (< 20 m water depth). In the tropical Pacific, ITCZ and SPCZ variability during the 20th century are clearly recorded as SST and sea surface salinity (SSS) variations in modern coral records (Cole et al., 1993; Linsley et al., 2006; Juillet-Leclerc et al., 2006; Wu et al., 2013; Todorović et al., 2024). Paired measurements of Sr/Ca and oxygen isotopes ($\delta^{18}O$) in skeletons of massive *Porites* spp. corals provide monthly resolved time series of SST and seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) (Gagan et al., 1998; Felis et al., 2009; 2020). Fossil corals provide insights into the history of seasonal and interannual variations in thermal and hydrologic balance during the Quaternary (Felis et al., 2004; 2020; Ayling et al., 2006; Asami et al., 2013; 2020). In the tropical South Pacific, last deglacial changes in SST seasonality and/or mean SST were reconstructed from fossil corals drilled by Integrated Ocean Drilling Program (IODP) Expedition 310 off Tahiti (Asami et al., 2009; Inoue et al., 2010; Felis et al., 2012; Knebel et al., 2024) and IODP Expedition 325 at the Great Barrier Reef (GBR) (Felis et al., 2014; Brenner et al., 2020). In general, most climate proxy records of fossil corals are from the Holocene and the last deglaciation. Thus, little is known about seasonal and interannual SST and SSS variability in the Pacific Ocean during glacial periods, due to limitations and difficulties in recovering fossil corals from these periods of substantially lower sea level than today.

Here, we present new Sr/Ca and $\delta^{18}O$ records of precisely U-Th dated fossil shallow-water corals recovered by IODP Expedition 310 (Camoin et al., 2007) off Tahiti in the central tropical South Pacific Ocean, aiming to reconstruct temperature and hydrology at the sea surface during past glacial conditions. These are the first monthly-to-bimonthly resolved coral proxy records of the penultimate glacial and the last glacial periods for the Pacific Ocean, and for the global ocean with respect to the penultimate glacial.

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2 Materials and methods

2.1 Study site

The island of Tahiti, located in the central South Pacific (S17°41′ W149°27′), is part of French Polynesia and characterized by a tropical climate (Fig. 1). At present, monthly average SST varies from 28.7 ± 0.5 °C in March to 26.5 ± 0.5 °C in August, with an annual mean of 27.6 ± 0.4 °C for 1979–2018 (1σ) (data from IRD and CRIOBE, Knebel et al., 2024). Monthly average SSS varies from 36.0 ± 0.2 in August–November to 35.7 ± 0.2 in March–May for 1980–2018 (data from SODA v.3, Carton et al., 2018). The climate of Tahiti is influenced by the SPCZ that extends south-eastwards from the WPWP toward the subtropical South Pacific. SPCZ activity is greater in austral summer than in winter (Brown et al., 2020) (Fig. 1). Oceanic areas affected by the SPCZ are characterized by high SST and enhanced precipitation, which results in a thicker mixed layer relative to the South Pacific Subtropical Gyre (de Boyer Montégut et al., 2004). In general, Tahiti has lower (higher) SST and higher (lower) SSS in austral winter (summer), related to contraction and weakening (expansion and strengthening) of the SPCZ (Locarnini et al., 2018; Zweng et al., 2018) (Fig. 1). On seasonal and interannual timescales, the activity and spatial extent of the SPCZ change in concert with variations of the ITCZ and ENSO (Meehl, 1987; Vincent, 1994; Juillet-Leclerc et al., 2006; Vincent et al., 2009).

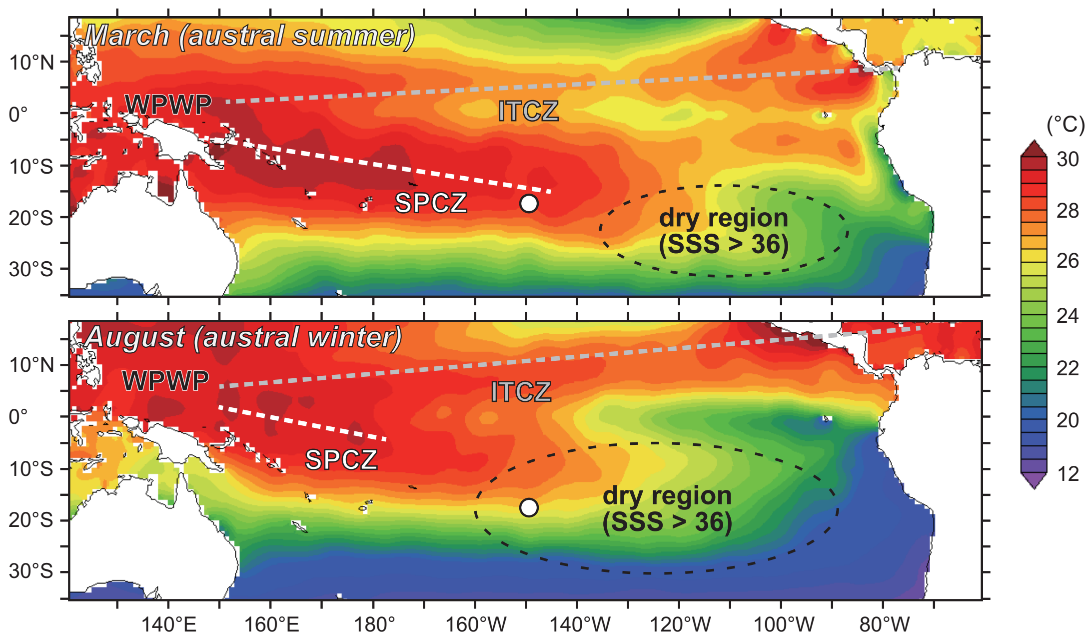

Figure 1. Study site in the Pacific Ocean. The coral samples used in this study were drilled at the fore-reef slope off the northern coast of the island of Tahiti (white dot) by IODP Expedition 310 (Camoin et al., 2007). Modern mean SST distributions during austral summer (March) and winter (August) for 1981–2010, approximate mean positions of the WPWP, ITCZ (gray dashed line), SPCZ (white dashed

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line), and the subtropical dry region (black dashed circle) with high sea surface salinity of >36 are shown. SST data from World Ocean Atlas 2018 (National Centers for Environmental Information, NOAA) (Locarnini et al., 2018; Zweng et al., 2018).

2.2 Samples and mineralogical screening

The three fossil massive corals (*Porites* spp.) used for this study were drilled offshore Tahiti (Tiarei) by IODP Expedition 310 (Camoin et al., 2007) (Fig. 2). Two penultimate glacial corals analyzed in this study (310-M0009D-25R-1W, 65-75cm; 310-M0009D-25R-2W, 43-51 cm and 57 cm) were U-Th-dated at 148.1 ± 0.9 ka and 152.7 ± 0.7 to 153.4 ± 0.5 ka (years before 1950 AD) (Thomas et al., 2009). A last glacial coral (310-M0009B-17R-1W, 44-53 cm) was located between two fossil corals in the core that yielded U-Th ages of 29.81 ± 0.07 ka and 29.66 ± 0.07 ka (Thomas et al., 2009). The mean of these two ages is used as best estimate for the age of our last glacial coral. Hereinafter, the coral ages are referred to as 148 ka and 153 ka during Marine Isotope Stage (MIS) 6b, just before the start of the penultimate glacial maximum (PGM), and 30 ka during MIS 3a, just before the start of the Last Glacial Maximum (LGM).

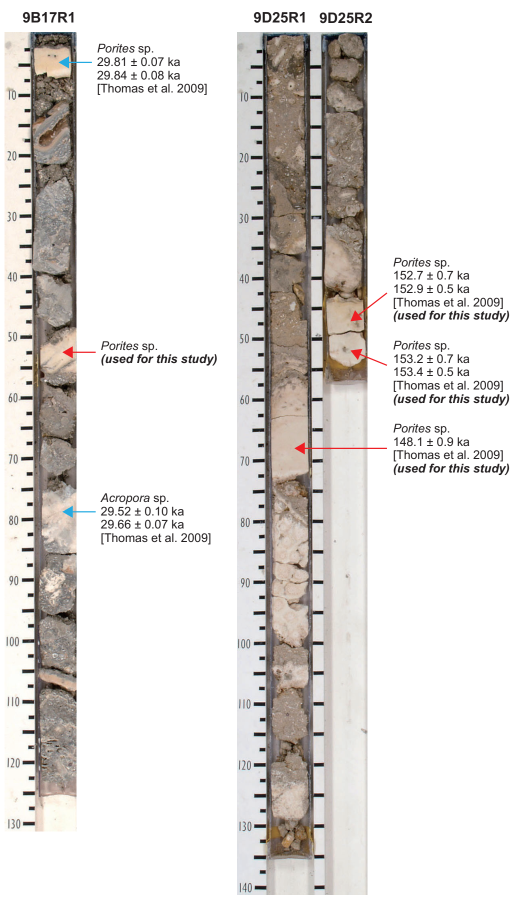

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Figure 2. Section photos of core 310-9B-17R-1, 310-9D-25R-1, and 310-9D-25R-2 drilled by IODP Expedition 310 (Camoin et al., 2007). Locations of coral samples dated in the previous study (Thomas et al., 2009) and used in this study are presented.

The samples were slabbed parallel to the coral growth axis, washed ultrasonically with milli-Q water, and dried in a clean booth at air temperature. X-radiographic images were taken using a multi soft X-ray film at Institute of Geology and Paleontology, Graduate School of Science, Tohoku University (IGPS, TU) (Fig. 3). For diagenesis screening, segment samples were taken at every ~1 cm along the transect for geochemical analysis. We conducted X-ray diffraction (XRD) analysis with a Phillips X'pert-MPD PW3050 system and scanning electron microscope (SEM) observations with Keyence 3D VE-8800 to check whether the original coral mineralogy and skeletal microstructure were preserved, following previous studies (Asami et al., 2009; 2013; 2020). For identification of aragonite or calcite cements, SEM images of well-preserved aragonite skeleton of modern corals were used. Results of XRD analysis and SEM observation are summarized at Table S1 and in Fig. S1 (see the Supplement). The samples (Core 310-M0009B-17R-1W, 44-53 cm, 310-M0009D-25R-1W, 65-75cm, and 310-M0009D-25R-2W, 43-51 cm and 57 cm) partially have aragonite and/or calcite cements. Consequently, we performed geochemical analyses on selected transects with well-preserved skeleton without any traces of diagenetic alteration (Fig. 3).

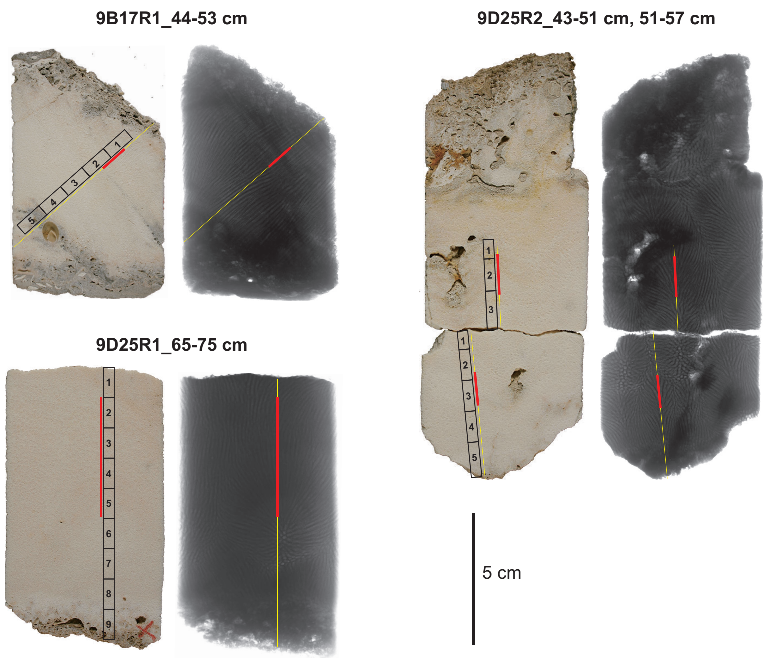

Figure 3. Coral slab photos and X-radiographic images of sample 310-9B-17R-1, 310-9D-25R-1, and 310-9D-25R-2. Areas with numbers are investigated for diagenesis screening. Growth direction and sampling track with well-preserved skeleton are indicated by yellow and red lines, respectively.

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2.3 Geochemical analyses

Powder samples from selected well-preserved skeletal portions with no evidence of diagenetic alteration were analyzed at 0.5 mm resolution for geochemistry. Carbon and oxygen isotope ($\delta^{13}C$ and $\delta^{18}O$) analysis for coral samples was performed using automated Kiel carbonate devices (Kiel III, Finnigan MAT) attached to Finnigan MAT252 and MAT253 mass spectrometers at JOGMEC (Japan Oil, Gas, and Metals National Corporation) and Kochi University. Isotopic ratios were reported in the conventional δ notation relative to the Vienna Peedee belemnite (VPDB) standard for coral samples, which was calibrated to the NBS-19 international standards. Precision and accuracy throughout the analysis was evaluated by replicate isotopic measurements of GSJ/AIST JCp-1 (aragonite; Okai et al. 2002), yielding the respective $\delta^{13}C$ and $\delta^{18}O$ values of −1.63 ± 0.02‰ and −4.72 ± 0.04‰ (1σ, n = 23).

Sr/Ca analysis was performed on splits of the coral powder samples for $\delta^{13}C$ and $\delta^{18}O$ analysis, using an inductively coupled plasma-mass spectrometer (XSeries II, ThermoFisher Scientific Inc.) at University of the Ryukyus. Each coral powder sample of 0.2 mg was dissolved in 5 mL of 0.5 mol/L high-purity HNO_3 solution diluted with ultrapure Milli-Q water. Internal standard elements (Sc, Y, and Yb) were added to all solutions to yield equal concentrations to control matrix effects and to correct for instrumental noise. Solutions were analyzed for ^{43}Ca, ^{44}Ca, ^{45}Sc, ^{87}Sr, ^{88}Sr, ^{89}Y, and ^{172}Yb in triplicate. Calibrations of the five gravimetric standard solutions yielded high linearity of r >0.99999 for respective elements. A reference solution gravimetrically matched to the Ca concentration of the coral sample solutions (ca. 15 ppm) was measured at intervals of three samples to correct for instrumental drift. The analytical method follows Asami et al. (2009, 2020). Based on replicate measurements of the JCp-1 (n = 141), precision for Sr/Ca was better than 0.30% relative standard deviation, yielding the average Sr/Ca of 8.840 mmol/mol in good agreement with a previously reported recommendation value (Hathorne et al., 2013).

In the geochemical records, the warmest and coldest month of a year were identified by the lowest and highest Sr/Ca of any given annual cycle. The sampling resolution (0.5 mm/sample) of our study corresponds to monthly-to-bimonthly resolution (12-to-6 subsamples/year), varying among years and coral individuals. To evaluate the averaging effects on Sr/Ca-derived SST reconstructions caused by such a different resolution, we estimated differences in SST attributable to different sample resolution (monthly vs. bimonthly) during winter and summer using the monthly OISST v2.1 time series (Huang et al., 2021). As a result, the difference can yield offsets of +0.07 ± 0.05 °C and −0.09 ± 0.06 °C in reconstructed winter and summer SSTs from fossil coral Sr/Ca records. The offset in SST seasonality is estimated to be −0.16 ± 0.07 °C. Consequently, the averaging effects on winter and summer values and seasonality for Tahiti corals do not largely affect our climatic interpretations presented in the discussion. The paleo-SST and -$\delta^{18}O_{sw}$ estimates with combined errors were calculated from calibrations and analytical errors by following previous studies (Cahyarini et al., 2008).

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3 Results and discussion

3.1 Coral Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ records

The coral Sr/Ca values range from 8.99 to 9.32 mmol/mol for 153 ka, 9.10 to 9.38 mmol/mol for 148 ka, and 9.10 to 9.32 mmol/mol for 30 ka, revealing about 6, 9, and 2.5 annual cycles, respectively (Fig. 4). The annual maximum and minimum Sr/Ca values average 9.28 ± 0.04 and 9.06 ± 0.06 mmol/mol for 153 ka, 9.31 ± 0.04 and 9.14 ± 0.03 mmol/mol for 148 ka, and 9.30± 0.03 and 9.12 ± 0.02 mmol/mol for 30 ka, corresponding to annual minimum and maximum SSTs recorded in winter and summer, respectively. The coral $\delta^{18}O$ ($\delta^{13}C$) values range from –2.67‰ (–0.84‰) to –1.88‰ (0.74‰) for 153 ka, from –2.42‰ (–1.25‰) to –1.58‰ (1.31‰) for 148 ka, and from –2.31‰ (0.02‰) to –1.87‰ (0.73‰) for 30 ka. Annual cycles in coral $\delta^{18}O$, and to some extent in coral $\delta^{13}C$, are in correspondence with the clear annual cycles in the Sr/Ca-SST proxy record. The interpretation of coral $\delta^{13}C$ on glacial-interglacial timescales is complex, as has been previously discussed for last deglacial GBR corals in the context of the global carbon cycle (Felis et al., 2022). Thus, in this study we focus on the paleoclimatic interpretation of coral Sr/Ca and $\delta^{18}O$. The average coral $\delta^{18}O$ values in annual minimum and maximum Sr/Ca-derived SSTs are –2.15 ± 0.14‰ and –2.33 ± 0.23‰ for 153 ka, –1.90 ± 0.12‰ and –2.24 ± 0.13‰ for 148 ka, and –1.95 ± 0.08‰ and –2.18 ± 0.12‰ for 30 ka, respectively. Moderate correlations between coral Sr/Ca and $\delta^{18}O$ records (r = 0.71–0.74, $p < 0.01$; Fig. 5) may indicate contributions by $\delta^{18}O_{sw}$ changes on seasonal to interannual timescales. This result is consistent with large amplitudes (~0.5‰) of the $\delta^{18}O_{sw}$ anomaly variations estimated from coral Sr/Ca and $\delta^{18}O$ records (Fig. 4), implying that interannual-scale SSS variations associated with the ITCZ and SPCZ variability may be observed in Tahiti during glacial periods similar to today. The skeletal growth rates based on Sr/Ca annual cycles are 4.3 mm/year for 153 ka, 4.8 mm/year for 148 ka, and 3.6 mm/year for 30 ka, which is substantially lower than 15.8 mm/year for modern Tahiti corals (Knebel et al., 2024). The lower growth rates are likely a result of lower SST during glacial periods.

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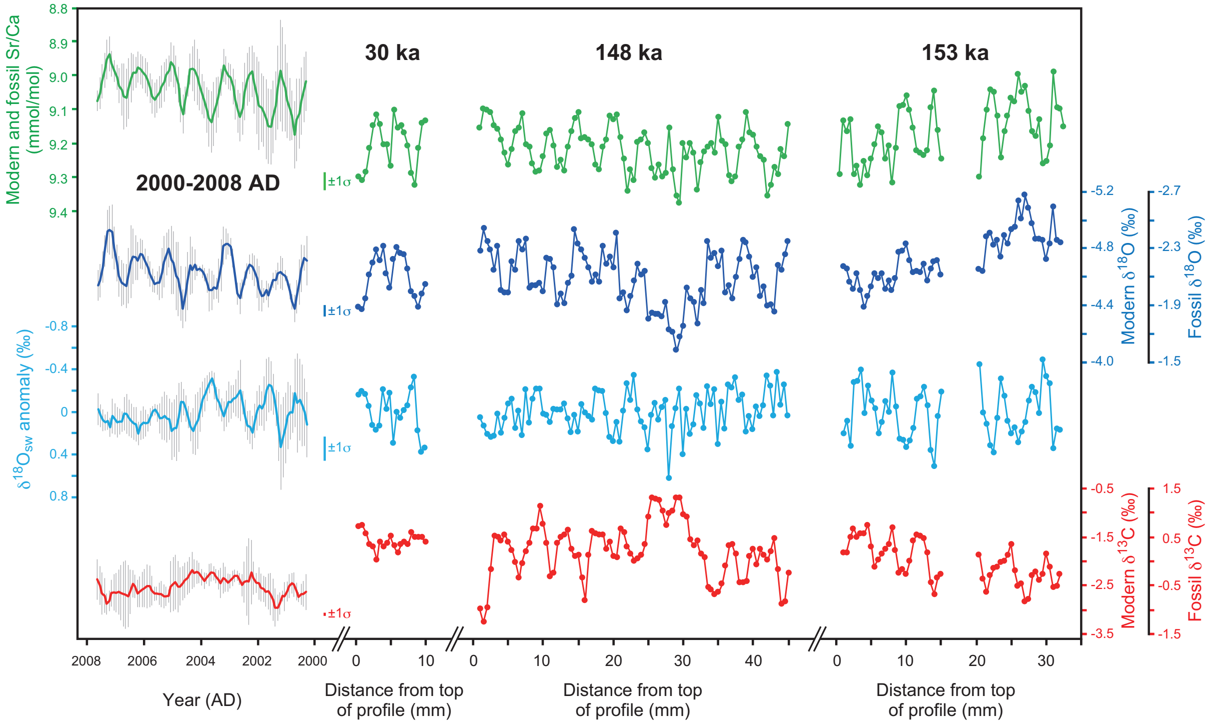

Figure 4. Records of Sr/Ca, $\delta^{18}O$, and $\delta^{13}C$ in fossil Tahiti corals of the penultimate glacial and last glacial. Seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) anomalies estimated from Sr/Ca and $\delta^{18}O$ records are presented. Annual cycles are clearly visible in the coral Sr/Ca-SST proxy records and coral $\delta^{18}O$-combined SST and hydrology proxy records, and to some extent in the coral $\delta^{13}C$ records. Coral ages are based on U-Th dating (Thomas et al., 2009). The growth direction is from right to left. For comparison, monthly resolved records of respective mean ± 1σ values from five modern Tahiti corals are shown (2000-2008 AD, data from Knebel et al., 2024). Horizontal bars represent analytical errors (±1σ).

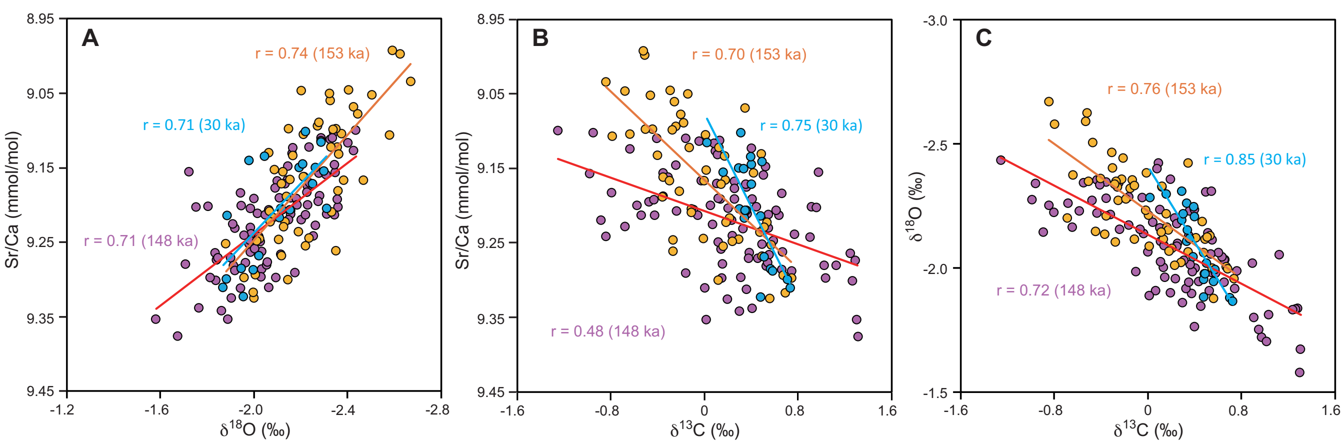

Figure 5. Cross plots of the geochemical records (A: Sr/Ca vs. $\delta^{18}O$, B: Sr/Ca vs. $\delta^{13}C$, C: $\delta^{18}O$ vs. $\delta^{13}C$) in fossil Tahiti corals (blue, 30 ka; purple, 148 ka; orange, 153 ka).

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3.2 Paleo-SST and -SSS estimates from coral geochemistry

Coral Sr/Ca is an established proxy for seawater temperature by previous examinations for *Porites* spp. corals (e.g., Smith et al., 1979; Corrège, 2006; Inoue et al., 2007). Paired measurements of coral Sr/Ca and $\delta^{18}O$ records enable estimation of both SST and $\delta^{18}O_{sw}$ (≈ salinity), by removing the temperature component of the coral $\delta^{18}O$ variation (e.g., Gagan et al., 1998; Cahyarini et al., 2008). Annual maximum and minimum Sr/Ca values in a fossil coral are assigned as annual minimum and maximum SSTs recorded in winter and summer, respectively. Compared with modern Tahiti corals (Knebel et al., 2024), the fossil corals have higher annual, summer, and winter Sr/Ca ($\delta^{18}O$) values by 0.12, 0.08, and 0.17 mmol/mol (2.35‰, 2.41‰, and 2.34‰) for 153 ka, by 0.18, 0.16, and 0.20 mmol/mol (2.54‰, 2.50‰, and 2.59‰) for 148 ka, and by 0.16, 0.14, and 0.19 mmol/mol (2.55‰, 2.56‰, and 2.55‰) for 30 ka (Table 1 and Fig. 4).

Table 1. Estimates of sea surface temperature (SST) and seawater oxygen isotope ($\delta^{18}O_{sw}$) values from penultimate glacial, last glacial, and modern corals at Tahiti.

Sample and age	RSL (m)*	Annual cycles (N)	Annual growth rate (mm/yr)	Coral Sr/Ca seasonality (mmol/mol)		Coral Sr/Ca (mmol/mol)	Coral $\delta^{18}O$ (‰)	Relative SST to today (°C)†	Relative $\delta^{18}O_{sw}$ to today (‰)§
Modern corals	0	31	15.8 ± 3.1	0.14 ± 0.05	*Annual*	9.05 ± 0.07	-4.61 ± 0.11		
(5 colonies)#					*Summer*	8.98 ± 0.04	-4.74 ± 0.09		
1999-2008 AD					*Winter*	9.11 ± 0.05	-4.49 ± 0.09		
Exp.310-9B-17R-1	-85	3	3.6 ± 0.9	0.18 ± 0.02	*Annual*	9.21 ± 0.02	-2.07 ± 0.06	-3.8 ± 1.5	+0.51 ± 0.13
(44-53 cm)					*Summer*	9.12 ± 0.02	-2.18 ± 0.12	-3.4 ± 0.8	+0.61 ± 0.15
~30 ka					*Winter*	9.30 ± 0.03	-1.95 ± 0.08	-4.4 ± 1.1	+0.40 ± 0.12
Exp.310-9D-25R-1	-115	9	4.8 ± 1.2	0.17 ± 0.03	*Annual*	9.23 ± 0.03	-2.07 ± 0.13	-4.0 ± 1.6	+0.42 ± 0.17
(65-75 cm)					*Summer*	9.14 ± 0.03	-2.24 ± 0.13	-3.7 ± 1.0	+0.45 ± 0.16
~148 ka					*Winter*	9.31 ± 0.04	-1.90 ± 0.12	-4.4 ± 1.2	+0.39 ± 0.15
Exp.310-9D-25R-2	-115	6	4.3 ± 0.8	0.23 ± 0.04	*Annual*	9.16 ± 0.04	-2.26 ± 0.16	-2.8 ± 1.7	+0.41 ± 0.20
(43-51 cm, 51-57cm)					*Summer*	9.06 ± 0.06	-2.33 ± 0.23	-2.0 ± 1.4	+0.62 ± 0.24
~153 ka					*Winter*	9.28 ± 0.04	-2.15 ± 0.14	-3.7 ± 1.2	+0.21 ± 0.16

*Relative sea level estimated from benthic foraminifera records (Waelbroeck et al., 2002)

†Corrected for seawater Sr/Ca changes (Stoll and Schrag, 1998; De Villiers, 1999) and for the offset of JCp-1 Sr/Ca mean values between Knebel et al. (2024) and this study. Relative SST was estimated using a Sr/Ca-SST equation (Knebel et al., 2024).

§Corrected for $\delta^{18}O_{sw}$ changes (Waelbroeck et al., 2002) and annual growth rate differences (Felis et al., 2003) and estimated using a $\delta^{18}O$-SST equation (Juillet-Leclerc and Schmidt, 2001)

#Data from Knebel et al. (2024)

For comparison between Sr/Ca-derived SST records, Sr/Ca measurements from different laboratories were corrected for the offset in the mean Sr/Ca value of the JCp-1 *Porites* coral standard (Okai et al., 2002; Hathorne et al., 2013) relative to the average value of 8.901 mmol/mol measured with the five modern Tahiti *Porites* corals (Knebel et al., 2024). Sea-level changes on glacial/interglacial timescales are responsible for variations in seawater Sr/Ca (Stoll and Schrag, 1998; Schrag et

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al., 2002) and $\delta^{18}O_{sw}$ (Waelbroeck et al., 2002). For each record, Sr/Ca data is corrected for seawater Sr/Ca changes using the sea level at a given age (Waelbroeck et al., 2002), assuming that seawater Sr/Ca was increased by 0.5% (Stoll and Schrag, 1998; Asami et al., 2009; Felis et al., 2012) relative to the present (8.539 mmol/mol: de Villiers, 1999) during the LGM. Paleo-SST differences relative to the present (2000–2008 AD) are estimated using the Sr/Ca-SST calibration slope of –0.050 mmol/mol/°C from modern Tahiti corals (Knebel et al., 2024). For $\delta^{18}O_{sw}$ estimation, coral $\delta^{18}O$ data is corrected for $\delta^{18}O_{sw}$ changes using the sea level at given age, as inferred from benthic foraminiferal $\delta^{18}O$ records (Waelbroeck et al., 2002), and for the $\delta^{18}O$ offset caused by difference in annual growth rate between modern and fossil corals using a previously established equation with r^2 value of 0.91 for eleven *Porites* spp. corals with growth rate of 2.0–15.2 mm/year (Felis et al., 2003). Paleo-$\delta^{18}O_{sw}$ differences relative to the present are estimated using the coral $\delta^{18}O$-SST calibration slope of –0.20 ‰/°C derived from *Porites* corals in a large tropical and subtropical region (Juillet-Leclerc and Schmidt, 2001).

Applying corrections for the inter-laboratory Sr/Ca offsets, for the seawater Sr/Ca and $\delta^{18}O_{sw}$ changes, and for the skeletal growth rate effects, improved SST and $\delta^{18}O_{sw}$ estimates relative to the present were inferred from the fossil Tahiti coral records of the penultimate glacial and last glacial (Table 1). The corresponding results indicate annual mean, summer, and winter SST and $\delta^{18}O_{sw}$ are 2.8 °C, 2.0 °C, and 3.7 °C lower (4.0 °C, 3.7 °C, and 4.4 °C lower) and 0.41‰, 0.62‰, and 0.21‰ higher (0.42‰, 0.45‰, and 0.39‰ higher) at 153 ka (at 148 ka) than today. At 30 ka, the respective values are 3.8 °C, 3.4 °C, and 4.4 °C lower and 0.51‰, 0.61‰, and 0.40‰ higher relative to today, which is similar to those of the 148 ka coral. Considering the inter-colony Sr/Ca variability of 0.023 mmol/mol (equivalent to 0.46 °C) from modern Tahiti corals (Knebel et al., 2024), the estimated SST differences are significant between the glacial periods and the present. These coral-based SST and $\delta^{18}O_{sw}$ estimates suggest the central tropical South Pacific Ocean around Tahiti was colder by 3–4 °C relative to today during MIS 6b (153 ka and 148 ka) and MIS 3a (30 ka). We note that these results represent upper estimates of the magnitude of cooling, although corrected for seawater Sr/Ca changes on glacial-interglacial timescales. Lower cooling estimates would have resulted if Sr/Ca-SST relationships for reconstructions of mean SST changes had been applied (Felis et al., 2009, DeLong et al., 2010; Gagan et al., 2012), as has been discussed in previous studies (Felis et al., 2012; 2014; Knebel et al., 2024). Ice volume corrected $\delta^{18}O_{sw}$ estimates suggest a higher SSS by +1 during these time intervals, if a modern salinity-$\delta^{18}O_{sw}$ relationship for South Pacific surface waters is applied (LeGrande and Schmidt, 2006). Our reconstructions are broadly consistent with subtropical South Pacific SST estimates for the LGM (3 to 4 °C lower than today) derived from isotope-enabled climate model simulations using data assimilation (Tierney et al., 2020), but are more pronounced than previous estimates (1 to 2 °C lower than today) (CLIMAP Project Members, 1976; MARGO Project Members, 2009).

3.3 Penultimate glacial mean climate in the tropical South Pacific

At Tahiti, fossil coral Sr/Ca records for key periods of the last deglaciation such as Heinrich Stadial 1 (HS1), Melt-Water Pulse 1A (MWP 1A), Bølling-Allerød (B-A), and the Younger Dryas (YD) are available (Asami et al., 2009; Hathorne et al., 2011; Felis et al., 2012; Knebel et al., 2024). For comparison, previously reported coral Sr/Ca values were corrected for

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inter-laboratory offsets as well as seawater Sr/Ca changes on glacial-interglacial timescales, and the time-weighted Sr/Ca averages within respective intervals are estimated following previous studies (Chuang et al., 2023; Knebel et al., 2024).

Results show that annual mean SST during the penultimate glacial is ~2.7 °C lower than the MWP 1A and B-A warming periods and ~1 °C lower than the HS1 and YD cooling periods. The most recent glacial maxima are the PGM (~140 ka, Lisiecki and Raymo, 2005) and the LGM (27–19 ka, Clark et al., 2009), corresponding to relative sea level lowstands of >120 m (Siddall et al., 2003; Yokoyama et al., 2018) (Fig. 6A). Our mean SST estimates from Tahiti coral Sr/Ca are broadly consistent with the global climate state at relative sea levels of about –115 m (ranging from –132 to –86 m) for MIS 6b during the penultimate glacial period and of –85 m (ranging from –99 to –71 m) for MIS3a during the last glacial period, just before the respective glacial maxima, the PGM and LGM (Waelbroeck et al., 2002) (Fig. 6B). Ice volume corrected mean $\delta^{18}O_{sw}$ values of 0.4‰ (153–148 ka) and 0.5 ‰ higher (30 ka) relative to the present (Table 1) demonstrate that the central tropical South Pacific surface ocean around Tahiti during MIS 6b and 3a had more positive mean $\delta^{18}O_{sw}$ values (equivalent to higher SSS by +1) than today.

At Rotuma, Fiji, Tonga, Rarotonga, and Tahiti in the tropical South Pacific, modern coral geochemical records reflect variations in SST, SSS, and precipitation associated with SPCZ variability (Linsley et al., 2006; Juillet-Leclerc et al., 2006; Wu et al., 2013; Todorović et al., 2024). Our $\delta^{18}O_{sw}$ estimates from fossil Tahiti corals are consistent with higher $\delta^{18}O$ values of precipitation in the tropical-to-subtropical South Pacific during the LGM, derived from isotope-enabled climate model simulations using data assimilation (Tierney et al., 2020). Thus, we suggest our fossil Tahiti coral data can be best explained by less active and/or northwestward-contracted SPCZ during the penultimate glacial and the last glacial periods. This was probably accompanied by a westward expansion of the subtropical South Pacific dry area with its higher salinity under the colder climates. Our paleoclimatic interpretation is largely consistent with modern oceanographic findings that the waters around the southeastern edge of the SPCZ are not only influenced by variations in the position of the SPCZ but also in the surface ocean salinity front that separates the warm/fresher waters in the northwest from the cool/saline waters in the southeast and east (Delcroix and McPhaden, 2002).

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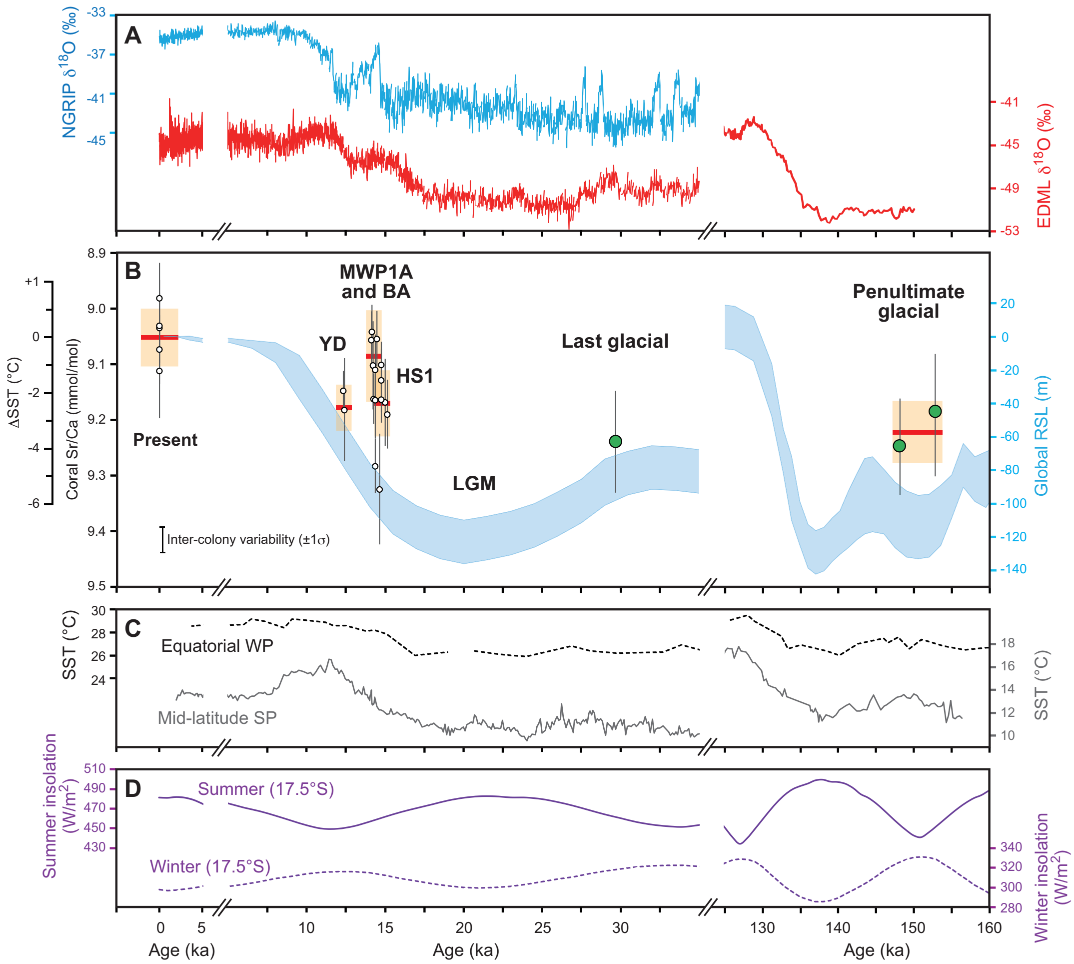

Figure 6. Temperature proxy records from Tahiti corals and paleoclimate records for the penultimate glacial, last glacial, last deglacial, and present. (A) Greenland (NGRIP, Rasmussen et al., 2006) and Antarctica (EDML, EPICA Community Members, 2006) ice core $\delta^{18}O$ records. (B) Annual mean Sr/Ca of sub-seasonally resolved modern and fossil Tahiti corals (white symbols, Asami et al., 2009; Hathorne et al., 2011; Felis et al., 2012; Knebel et al., 2024; green, this study). Vertical bars: Mean seasonality. Red horizontal bars: Weighted average of colony means for given interval (penultimate glacial, HS1: Heinrich Stadial 1, MWP1A: Melt-Water Pulse 1A, BA: Bølling–Allerød, YD: Younger Dryas, present: 2000-2008 AD) with uncertainty (CE: combined error, light orange area). The JCp-1 Sr/Ca value representative for the coral Sr/Ca values shown is 8.901 mmol/mol (Knebel et al., 2024). Corrected for seawater Sr/Ca changes by sea-level dependency at a given age (Waelbroeck et al., 2002) assuming seawater Sr/Ca 0.5% higher than present (8.539 mmol/mol) at the Last Glacial Maximum (LGM) (Stoll and Schrag, 1998; De Villiers, 1999). Reconstructed SST anomaly relative to today based on modern Tahiti coral Sr/Ca-SST relationship (–0.050 mmol/mol/°C, Knebel et al., 2024). The inter-colony variability (±1σ) estimated from modern Tahiti corals (Knebel et al., 2024) is shown. The light blue belt denotes a range of maximum and minimum global sea level inferred from benthic foraminiferal $\delta^{18}O$ records (Waelbroeck et al., 2002). (C) Equatorial western Pacific SST from foraminiferal Mg/Ca (ODP 806B,

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Medina-Elizalde and Lea, 2005) and South Pacific mid-latitude SST from alkenones (MD97-2120, Sikes and Volkman, 1993; Pahnke and Sachs, 2006). (D) Summer and winter insolation at the latitude of Tahiti (17.5°S) (Laskar et al., 2004).

Our fossil coral records provide snapshots of tropical South Pacific climate around 153–148 ka and at 30 ka (Fig 6A). The weighted average SST reconstruction from our coral Sr/Ca records shows that the mean climate condition around Tahiti (17.5°S) is 3.4 ± 1.1 °C colder for 153–148 ka than the present (Fig. 6B). Foraminiferal Mg/Ca records from ODP core 806B at 0.3°N (Medina-Elizalde and Lea, 2005) and alkenone records from MD97-2120 core at 45.5°S (Sikes and Volkman, 1993; Pahnke and Sachs, 2006) show a cooling by <2 °C in the WPWP and ~4 °C in the mid-latitude South Pacific at that time (Fig. 6C). These results may indicate stronger latitudinal and/or zonal mean SST gradients in the South Pacific during the penultimate glacial (MIS 6b) relative to today. During the last glacial period (MIS3a), the three paleoclimate proxy records show a lower SST by ~3 °C (0.3°N), 3.8 ± 1.5 °C (17.5°S), and ~6 °C (45.5°S) than the present, possibly indicating the mean SST gradient was more pronounced in the subtropical to mid-latitude South Pacific relative to the penultimate glacial period. These lines of evidence for the stronger zonal SST gradients imply that latitudinal winds were probably more pronounced during glacial cold periods, which is supported by results of climate simulation experiments and dust fluxes in ice cores (Lambert et al., 2008; Cao et al., 2019; Krätschmer et al., 2022).

3.4 Seasonal SST and SSS differences: Paleoclimatological implications

The seasonal Sr/Ca amplitude is calculated using individual data for modern and fossil corals in the same manner and shown as the averages of corals for respective age intervals (Table 1). Our Tahiti coral Sr/Ca seasonality of 0.23 and 0.17 mmol/mol at 153–148 ka and 0.18 mmol/mol at 30 ka is larger than that previously reported for HS1 (0.13 mmol/mol), B-A (0.12 mmol/mol), and the present (0.14 mmol/mol) (Knebel et al., 2024) (Fig. 6B). The seasonality difference can be explained by a SST decrease that is larger in austral winter by 0.8–1.7 °C and 1.0 °C compared to austral summer at 153–148 ka and at 30 ka relative to present, respectively (Table 1). The seasonal thermal difference at Tahiti may indicate a stronger latitudinal gradient of winter SST in the central tropical-to-subtropical South Pacific relative to today (Fig. 1). Furthermore, we found that the $\delta^{18}O_{sw}$ (salinity) increase relative to the present is 0.1–0.4‰ (equivalent to 0.1–0.9) and 0.5‰ (equivalent to 0.5) larger in the austral summer than in austral winter at 153–148 ka and 30 ka (Table 1). The hydrological differences during the seasons suggest that the surface ocean around Tahiti experienced higher evaporation (lower precipitation) and/or northwestward advection of saltier waters from the eastern subtropics in austral summer rather than winter at that time.

The SPCZ is a diagonal band of intense rainfall and deep atmospheric convection extending from the WPWP to the subtropical South Pacific (Fig. 1). The area to the east of the SPCZ is characterized as south-east Pacific dry area because of being persistently free of deep convective rainfall, possibly linked to orographic forcing from the Andes via feedbacks involving subsidence of low specific humidity air, low clouds and cooler SSTs (Takahashi and Battisti, 2007). The extent of this dry zone influences the extent of the eastern edge of the SPCZ. Consequently, our results of reconstructed SST and $\delta^{18}O_{sw}$ changes during the penultimate and last glacial from fossil Tahiti corals can be best explained by lower activity of the

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SPCZ and/or its contraction to the northwest, and an accompanied expansion of the South Pacific subtropical dry area during glacial periods.

Previous work on geochemical records of fossil Tahiti corals reported an increased Sr/Ca-derived SST seasonality of 0.17±0.02 mmol/mol during the YD, a pronounced cold interval of the last deglaciation in the Northern Hemisphere and Tahiti (Asami et al., 2009), which was suggested to be resulted from reduced thickness of the mixed layer and an enhanced influence of the South Pacific Subtropical Gyre due to a weakening of SPCZ activity (Knebel et al., 2024). Interestingly, our reconstructed weighted average coral Sr/Ca seasonality of 0.20 ± 0.05 mmol/mol at 153–148 ka is similar to or larger than that during the YD period (Fig. 6B), which may indicate a thinner mixed layer around Tahiti during the penultimate glacial period. This interpretation is further supported by variations in orbital parameters that cannot explain the increased temperature seasonality at Tahiti during these time intervals. Austral summer and winter insolation at Tahiti (17.5°S) were relatively low and high, respectively, during the MIS 6b as well as the YD, with a smaller seasonality relative to today (Laskar et al., 2004) (Fig. 6D). We speculate that SST and SSS variability around Tahiti under glacial conditions were strongly influenced by a weakening and/or contraction of the SPCZ and expansion and/or westward migration of the South Pacific dry area, as reflected in our coral-based evidence for larger SST seasonality and higher reconstructed mean $\delta^{18}O_{sw}$ (salinity) values during the penultimate glacial period.

4 Conclusions

We present new monthly-to-bimonthly resolved Sr/Ca and $\delta^{18}O$ records of well-preserved fossil Tahiti corals recovered by IODP Expedition 310 to reconstruct annual mean, summer, and winter SST and $\delta^{18}O_{sw}$ at 153 ka and 148 ka (MIS 6b) and 30 (MIS 3a) in the tropical-to-subtropical South Pacific Ocean. When compared with records from last deglacial and modern Tahiti corals (Knebel et al., 2024), our coral proxy records indicate that penultimate glacial and last glacial climate around Tahiti is characterized by colder and more saline conditions at the sea surface. The coral-based reconstructions reveal differences in thermal and hydrological seasonal conditions that are best explained by SST and SSS anomalies associated with spatial variations in the SPCZ and the South Pacific subtropical dry area. These conditions show similarities to those previously inferred from Tahiti corals for the YD cold period (Knebel et al., 2024). Given potential uncertainties in inter-colony $\delta^{18}O$ variability (Sayani et al., 2019), more fossil coral samples are needed to quantitatively evaluate the significance of $\delta^{18}O_{sw}$ differences between the past and present and to verify our paleoclimatological suggestions. Long-lived fossil corals are also required to discuss the respective components of seasonal, interannual, and decadal variations in paleo-SST and -$\delta^{18}O_{sw}$ records strongly relating to the ITCZ and SPCZ variability associated with ENSO. To date, there is only one such record documenting pronounced interannual variability in tropical South Pacific temperatures at typical ENSO periods during Heinrich Stadial 1 of the last glacial (Felis et al., 2012). Nevertheless, our combined coral-based results of tropical South Pacific SST and $\delta^{18}O_{sw}$ characteristics under glacial conditions can help to constrain model simulations of past and future climate change. Recently, IODP Expedition 389 "Hawaiian Drowned Reefs" drilled coral reefs in the central tropical-subtropical North Pacific Ocean to reconstruct glacial-interglacial environmental changes over the last 500,000 years (Webster et al., 2024). Future, integrated interpretations of coral-based climate reconstructions from Hawaii and Tahiti fossil corals will provide a more thorough understanding of changes in seasonality, interannual variability, and mean climate changes across the central tropical-to-subtropical North and South Pacific during the penultimate glacial and last glacial periods.

Data availability. Coral data generated from this study are available at the World Data Center PANGAEA (https://www.pangaea.de/). Correspondence and requests for data and materials should be addressed to R.A.

Supplement. The supplement material (Table S1 and Fig. S1) is available online.

Author contributions. R.A. and T.F. designed the study. R.A. conducted experiments, performed data analyses, and wrote the original draft. T.F. revised the original draft. R.S., M.M., and Y.I. collaborated with experiments. All authors discussed the results and edited the manuscript.

Competing interests. The authors have no conflict of interest to declare.

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