The Northwest Pacific corals unravel the NPGO- and Victoria Mode-related temperature back to the 19th century

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Abstract. Atmospheric and oceanic phenomena in the Pacific Ocean, such as the North Pacific Gyre Oscillation (NPGO) and the Victoria Mode (VM), have significant implications for global climate variability through their linkage with temperature variability in the Central Pacific (CP). The NPGO and VM manifest are defined based on sea surface height and basin-wide sea surface temperature anomaly patterns in the North Pacific, respectively, but they are often closely coupled. Although recent studies have drawn attention to their connection with temperature variability in the CP, its historical variability remains poorly understood due to limited instrumental observations. Because coral Sr/Ca records directly reflect temperature variability, their archives can capture signals of the temperature expression of the dynamically linked mode between NPGO and VM (i.e., NPGO–VM-related temperature variability). Here, we present a long-term reconstruction of NPGO–VM-related temperature variability based on a coral Sr/Ca temperature proxy from the Northwest Pacific (NWP), covering the period from 1798 to 2014 Common Era. The coral-inferred temperature record closely aligns with temperature variability in the CP, indicating an extra-tropical propagation of NPGO–VM-related temperature variations from the CP to the NWP via an ocean-atmosphere bridge. Our reconstruction identifies a pronounced negative-NPGO/positive-VM phase (cool-temperature in the NWP) during the 1860s–1900s, and a positive-NPGO/negative-VM phase (warm-temperature in the NWP) during the 2000s–2010s. We also find a significant correlation between temperature variability in the CP and interannual to decadal NPGO–VM variability throughout the past 200 years. This relationship lasted from the early 20th century until 2014, with the exception of the period from the 1970s to the 1990s, and strengthened and sustained from the 2000s onward. Given the strong linkage between the NPGO–VM and the temperature anomalies in the CP, as well as the projected increase in CP-centred climate variability under future warming scenarios, the prominence of the NPGO–VM in the North Pacific and beyond is expected to intensify.

1 Introduction

Atmospheric and oceanic phenomena in the Pacific Ocean play a significant role in shaping global climate systems, including variations in sea surface temperature (SST) and ocean circulation. Global SST variations are known to be closely associated with Pacific climate phenomena (Messié and Chavez, 2011), such as the El Niño-Southern Oscillation (ENSO) (McPhaden et al., 2006; Philander, 1983), the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008). Recent studies have further classified ocean-atmosphere interactions in the equatorial Pacific into two flavours based on the longitudinal position of the temperature anomalies in the Eastern Pacific (EP; 5° S–5° N, 150–90° W) and the Central Pacific (CP; 5° S–5° N, 160° E–150° W) (Ashok et al., 2007; Kao and Yu, 2009; Larkin and Harrison, 2005; Lee and McPhaden, 2010; Yeh et al., 2009). These phenomena and their associated SST variability have teleconnections on global climate, influencing weather patterns, ecosystems, and socio-economic systems worldwide.

The NPGO is a mode of decadal-scale climate variability in the North Pacific, first introduced by Di Lorenzo et al. (2008). The index for NPGO (Di Lorenzo et al., 2008) quantifies variations in the strength of the central and eastern branches of the clockwise North Pacific gyre circulation, available back to 1950 Common Era (CE). Dynamically, the NPGO is defined as the second principal component (i.e., the second empirical orthogonal function; EOF2) of sea surface height anomalies (SSHa) in the central-to-eastern North Pacific. The corresponding EOF2 spatial pattern exhibits a meridional dipole-like structure, with a nodal line around 40º N, reflecting large-scale wind-driven gyre circulation changes (Di Lorenzo et al., 2008; Chhak et al., 2009). The NPGO is primarily forced by boreal wintertime wind-stress curl anomalies associated with the North Pacific Oscillation (NPO; Rogers, 1981; Walker and Bliss, 1932), with oceanic adjustment leading to circulation and SSH anomalies that typically peak from boreal late winter to spring, and its effects can be observed even in early summer (Chenillat et al., 2012). The dipole structure of the NPGO closely resembles that of the Victoria Mode (VM) (Bond et al., 2003), which is defined as the EOF2 of basin-wide sea surface temperature anomalies (SSTa) over the North Pacific (Di Lorenzo et al., 2008). The VM represents a dominant mode of extratropical SST variability on interannual-to-decadal scales, particularly during boreal winter and spring (Ding et al., 2015; Yu and Kim, 2011; Wen et al., 2024). In contrast to the dynamical ocean-circulation-based NPGO, the VM primarily reflects a thermodynamic surface response to atmospheric forcing by the NPO (Ding et al., 2015), through surface heat fluxes and Ekman advection.

Beyond the similarity in their dipole-like spatial structures observed in the EOF2 of SSHa and SSTa, the NPGO and VM exhibit coherent temporal variability (Fig. A1), particularly on interannual-to-decadal timescales. This coherence arises because both modes are fundamentally driven by NPO-related atmospheric forcing. In this sense, the NPGO and VM can be regarded as dynamically linked components of a broader extratropical ocean–atmosphere system. The NPO has also been identified as a precursor to ENSO events via the seasonal footprinting mechanism, linking subtropical sea level pressure (SLP) anomalies to tropical Pacific variability (Vimont et al., 2001; Vimont et al., 2003). Both the NPGO and VM are thought to be tightly coupled with CP-ENSO dynamics, forming bidirectional links that connect extratropical and tropical Pacific climate variability (Di Lorenzo et al., 2010; Di Lorenzo, 2013; Ding et al., 2015; Qi and Mao, 2022). These modes also play important

roles in regional climate variability, including East Asian hydrology (e.g., Ye et al., 2016) and the Indian summer monsoon (e.g., Zhang et al., 2024a; Zhang et al., 2024b). Despite growing understanding of these mechanisms and their impacts, the long-term interactions and variability among the NPGO, VM, and CP-ENSO remain poorly understood due to the limited temporal coverage of instrumental and satellite observations. Addressing this limitation requires longer-term pre-instrumental archives, such as paleoclimate proxy records.

Modern and fossil reef-building corals can provide high temporal resolution archives of paleoclimatology on scales that can cover more than several hundred years (e.g., Abram et al., 2020; Cobb et al., 2003; D'Olivo et al., 2024; Hendy et al., 2002; Kawakubo et al., 2017; Quinn et al., 1998; Tangri et al., 2018). Notably, the ratio of strontium to calcium (Sr/Ca) in coral aragonite skeletons ($CaCO_3$) has been used as a proxy for paleo-temperature variability (e.g., Cahyarini et al., 2014; D'Olivo et al., 2024; Felis et al., 2018). Therefore, coral Sr/Ca records can capture signals of the oceanic expression of the dynamically linked mode between NPGO and VM and potentially reconstruct it at the century scale, extending the observational record or indices. In the Pacific, long-term coral records that complement or extend instrumental data are primarily concentrated in the tropics (Cobb et al., 2003; Cobb et al., 2013; Cole et al., 1993; D'Olivo et al., 2024; McGregor et al., 2013; Nurhati et al., 2011; Rafter et al., 2017; Sanchez et al., 2016). Although several studies have attempted to reconstruct the NPGO mode in the past (Nurhati et al., 2011; Rafter et al., 2017; Sanchez et al., 2016), none have focused on VM variability and NPGO- or VM-related temperature variations propagated extra-tropically from the CP. Focusing on the Northwest Pacific (NWP), paleoclimatic coral archives have mostly been used for East Asia monsoon reconstructions based on skeletal oxygen isotope ratio records ($\delta^{18}O$) (Garas et al., 2023; Kajita et al., 2017; Morimoto et al., 2007; Watanabe et al., 2014) and temperature reconstructions based on skeletal Sr/Ca records (Kawakubo et al., 2017; Felis et al., 2010). Here, we introduce a new coral-based long-term temperature archive from the NWP. We compare our coral record with previously published coral Sr/Ca-temperature records and then investigate a linkage among our new coral-based Sr/Ca-temperature record, the variabilities of the CP temperature, NPGO, and VM. This study presents the first coral-based reconstruction of NPGO–VM-related temperature variability derived from the NWP, extending back to the 19th century.

2 Methods

2.1 Study site and coral core collection

We collected three coral cores from Kikai Island, Kagoshima Prefecture, Japan, which is located in the NWP (Figs. 1 and A2). In June 2015 CE, three *Porites* coral cores were drilled from two colonies using an air drill with a 7.6 cm diameter core barrel at less than 5 m water depth in Shiomichi Bay, northeast of Kikai Island (28.338° N, 130.009° E). One core (Core-1) was collected from a living colony, and the others (Core-2 and Core-3) were collected from a microatoll-shaped sub-fossil colony. The two colonies were located adjacent to each other.

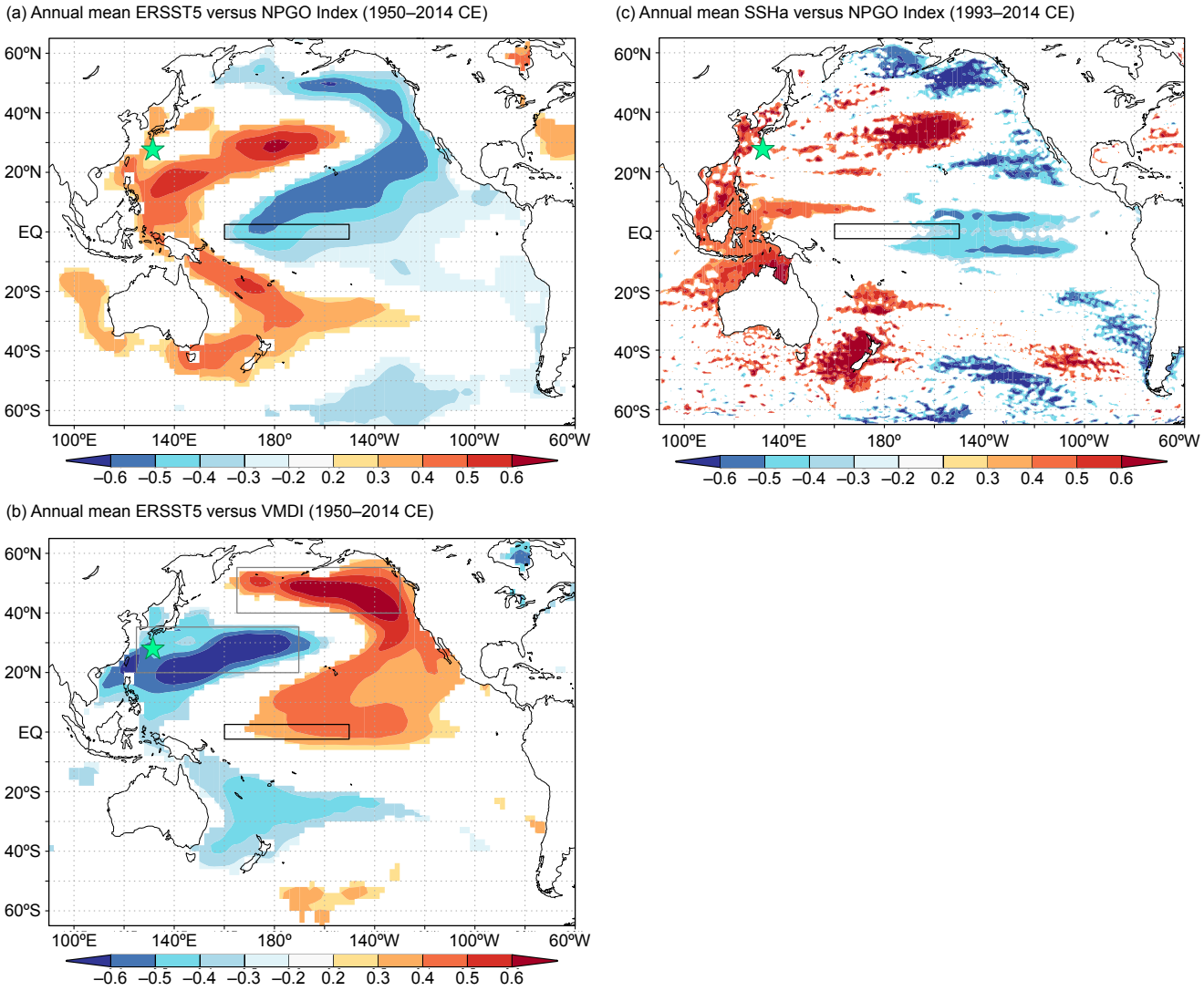

Figure 1. Spatial distribution of the NPGO and VM patterns shown in SST or SSH fields.

(a) Field correlation map between the annual mean SST time series (ERSST5; Huang et al., 2017) and the NPGO Index (Di Lorenzo et al., 2008) from 1950 to 2014 CE. (b) Field correlation map between the annual mean SST time series (ERSST5; Huang et al., 2017) and the Victoria Mode Dipole Index (VMDI; Wen et al., 2024, calculated using ERSST5, grey boxes) from 1950 to 2014 CE. (c) Field correlation map between the annual mean SSHa time series (Copernicus 0.25° × 0.25°, Copernicus Climate Change Service) and the NPGO Index from 1993 to 2014 CE. All correlations are computed using detrended data. Only correlations with *p*-values < 0.1 are colour-coded. The original figures in each panel were computed using the web application KNMI Climate Explorer (https://climexp.knmi.nl/) and plotted using GrADS (v2.2.1). The location of the coral sampling site (Kikai Island, Kagoshima, Japan) is marked by a star. The black box indicates the CP region (5° S–5° N, 160° E–150° W).

2.2 Sample preparation and coral skeletal Sr/Ca analysis

All cores were cut into 5 mm thick slabs. The slabs were rinsed several times with distilled water in an ultrasonic bath and then dried at 50 °C for 24 h. X-radiographs (Fig. A3) were taken using a digital X-ray scanner, following the method described by Ito et al. (2020). Clear annual bands were observed in the X-radiographs of Core-1 and Core-3 but not in Core-2 (Fig. A3).

Preservation of pristine skeletal aragonites in all specimens was confirmed by powder X-ray diffraction analysis at Hokkaido University (Fig. A4) and by microscopic observations at the KIKAI Institute for Coral Reef Sciences (Fig. A5).

Analytical paths were determined to follow the extending corallites and their growth direction along the major growth axis visible in the X-radiographs (Fig. A3) and on the slab surfaces. Skeletal powder samples for geochemical analysis were obtained using a precise microsampling technique with a 0.8 mm diameter micro-drill mounted on a semi-manually controlled XY stage. Each sample was collected at 1.2 mm intervals with a drilling depth of 1.0 mm. After each sampling, the milled area was cleaned with compressed air to avoid cross-contamination.

Coral skeletal Sr/Ca analysis was performed by inductively coupled plasma optical emission spectrometry (ICP-OES; iCAP 6200 Duo, Thermo Scientific) equipped with an autosampler (ASX-260, Teledyne CETAC Technologies) installed at Hokkaido University, following the method described by Watanabe et al. (2020). The coral Sr/Ca time series from 1989 to 2015 CE (part of Core-1) was previously documented by Kajita et al. (2017). Powdered samples (150 ± 10 μg) were dissolved in 250 μL of 25 % high-purity nitric acid and subsequently diluted with ultrapure water (Milli-Q water, 18.2 Ω cm at 25 ºC, Merck Millipore). We calibrated Sr/Ca using the intensity-intensity ratio method (de Villiers et al., 2002) with five matrix-matched standard solutions. The JCp-1 solution (Okai et al., 2002) was measured as a reference material after every five sample measurements to correct for instrumental drift. As reported by Watanabe et al. (2020), the Sr/Ca value of the JCp-1 reference material was 8.838 ± 0.009 mmol mol^{-1} (1σ). Analytical uncertainty was typically 0.1 % relative standard deviation (%RSD, 1σ).

2.3 Chronology and seasonal definition

For the sub-fossil specimens (Core-2 and Core-3), three skeletal fragments were subsampled for uranium–thorium (U–Th) dating (174–413 mg each; Fig. A3). High-precision U–Th dating was conducted at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), National Taiwan University. U–Th chemistry was performed on a class-100 bench in a class-10,000 clean room (Shen et al., 2003; Shen et al., 2008). Skeletal U and Th isotopic compositions were determined using a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS; NEPTUNE, Thermo Fisher) (Shen et al., 2012). The decay constants used were from Cheng et al. (2013) for ^{230}Th and ^{234}U, and from Jaffey et al. (1971) for ^{238}U.

The age model was established based on coral Sr/Ca seasonal cycles, the Optimum Interpolation Sea Surface Temperature (OISST v2.1; Huang et al., 2021, monthly resolved and converted from daily data, see Sect. 2.4), annual density bands, and U–Th dating results (for sub-fossil specimens only). Core-2 showed clear annual cycles in the coral Sr/Ca record without

interruption (e.g., no breakdown or abrupt shifts in seasonality), although its annual density bands were indistinct. Therefore, for Core-2, we developed an age model based on the annual cycles in the coral Sr/Ca record and the U–Th dating result. For overlapping periods between cores (1926–1931 CE between Core-1 and Core-2; 1884–1886 CE between Core-2 and Core-3; Fig. A6), the coral Sr/Ca records were recomputed into averaged values for each year. We used tie points to connect the highest (lowest) Sr/Ca values and the coolest (warmest) temperature values derived from the OISST data to establish each year, following the method of Ito et al. (2020). Based on the seasonal cycle in the OISST dataset from September 1981 to June 2015 CE, the annual coolest and warmest temperatures occur in February and August, respectively. For the period prior to August 1981 CE, the age model was established using tie points to connect the highest (lowest) Sr/Ca values and February (August). This method, an age-model approach using an artificial time series composed of repeating mean monthly temperatures, is commonly applied in coral geochemical studies (e.g., Charles et al., 1997; Felis et al., 2000; Pfeiffer et al., 2009; DeLong et al., 2014; Cahyarini et al., 2021); however, this approach can produce approximately 1–2 months of error in any given year for the period prior to the instrumental era. To minimise the influence of this uncertainty on our analysis, we used monthly interpolated summer and winter coral Sr/Ca records, defined by averaging three consecutive months centred on the warmest and coolest months, respectively, based on SST climatology (see Sect. 2.5).

2.4 Instrumental datasets and indices

We used instrumental datasets and climate indices to compare with coral geochemical records. Monthly data from the NOAA Extended Reconstructed Sea Surface Temperature Version 5 (ERSST5; Huang et al., 2017) were obtained from the grid cell covering the coral sampling site (27–29° N, 129–131° E; referred to as "Kikai-SST_{ERSST5}") and from the CP (5° S–5° N, 160° E–150° W; referred to as "CP-SST_{ERSST5}") for the period 1900–2014 CE. The abbreviations of these instrumental datasets are listed in Table A1. An annual SSHa time series (0.25° × 0.25° spatial resolution) from the Copernicus Climate Change Service was obtained for the period 1993–2014 CE. Both SST and SSHa data were downloaded via the KNMI Climate Explorer (https://climexp.knmi.nl/). Additionally, the monthly NPGO Index (Di Lorenzo et al., 2008) for the period 1950–2014 CE was obtained from the NPGO website (http://www.o3d.org/npgo/index.html). Following Wen et al. (2024), the Victoria Mode Dipole Index (VMDI) was calculated as the difference in SSTa between the northeastern North Pacific (40–55° N, 165° E–129° W) and the southwestern North Pacific (20–35° N, 125° E–170° W) for the period 1900–2014 CE. The NPO dataset for the period 1950–2014 CE was calculated from the Hadley Centre Sea Level Pressure dataset (HadSLP2r, Allan and Ansell, 2006; 30–65º N, 160º E–140º W) using the empirical orthogonal function method of Trenberth and Hurrell (1994) at KNMI Climate Explorer.

For establishing the age model for the coral geochemical record, we used the OISST v2.1 dataset (Huang et al., 2021, monthly resolved and converted from daily data) covering Kikai Island as a reference temperature product that reflects local water temperatures at high spatial resolution (0.25º × 0.25º grid) (see Sect. 2.3 for details of the age model method). A comparison between the instrumental temperature datasets employed in this study (OISST v2.1 and ERSST5) is shown in Fig. A7,

indicating a statistically significant correlation at the 99 % confidence level (r = 0.99, n = 406, monthly resolution, for the period 1981–2014 CE).

2.5 Converting coral Sr/Ca record (Kikai-coral Sr/Ca) into Sr/Ca-inferred temperature (ºC, centred, Kikai-SST_{coral})

Based on the established age model (Sect. 2.3), we obtained a continuous 217 year coral Sr/Ca record, referred to as "Kikai-coral Sr/Ca." The dataset was then interpolated to a monthly resolution. From this monthly resolved dataset, three derived time series were constructed. First, three-month-averaged Sr/Ca values centred on the lowest and highest Sr/Ca values in each year, corresponding to boreal summer and winter, respectively, and are referred to as "Kikai-coral Sr/Ca_{summer}" and "Kikai-coral Sr/Ca_{winter}." Second, annual mean Sr/Ca values were calculated by averaging the Sr/Ca record from one winter peak to the subsequent winter peak; this time series is referred to as "Kikai-coral $Sr/Ca_{annual\ mean}$." The abbreviations of these time series are listed in Table A1.

We converted Kikai-coral Sr/Ca_{summer} and Kikai-coral Sr/Ca_{winter} (unit in mmol mol^{-1}) into temperature (unit in ºC) using a Monte–Carlo technique that accounts for both coral Sr/Ca analytical errors and Sr/Ca-temperature slope uncertainties (Watanabe and Pfeiffer, 2022). For the Monte–Carlo simulation, we adopted four previously published Sr/Ca-temperature slopes derived from corals at Kikai Island (Fig. A8, Kajita et al., 2017; Kawakubo et al., 2014; Morimoto et al., 2007; Watanabe et al., 2020) in order to encompass potential intercolonial differences in the slope at this site. The resulting coral-based temperature record is hereafter referred to as "Kikai-SST_{coral}." When the record was calculated using Kikai-coral Sr/Ca_{summer} (Kikai-coral Sr/Ca_{winter}), the dataset is referred to as "Summer Kikai-SST_{coral} (Winter Kikai-SST_{coral})." This record is presented as a 'centred' time series, where the mean value has been subtracted from the data. Centring is a standard statistical procedure (Draper and Smith, 1981) and has been commonly used in previous studies of coral-based temperature reconstructions (e.g., Cahyarini et al., 2008; Felis et al., 2018; Garas et al., 2023; Xu et al., 2015).

2.6 Statistical analysis

We tested the significance of the differences in coral Sr/Ca records for overlapping periods between Core-1 and Core-2, and between Core-2 and Core-3, using t-tests. The significance of variance differences in summer and winter Sr/Ca values among cores was tested using Levene's test. For time series analysis, we applied three types of temporal filters, based on the results of multi-taper spectral analyses for each dataset, including the NPGO Index and the VMDI datasets (Fig. A9, see Sect. 3.1): (1) an 8–30 year bandpass filter, (2) a 10–30 year low-pass filter, and (3) an 8 year low-pass filter. The 8 year low-pass filter (bandwidth = 0.000–0.125) has been commonly used in previous NPGO studies (Di Lorenzo et al., 2010; Ding et al., 2015; Nurhati et al., 2011). To remove both high- and low-frequency variability, an 8–30 year bandpass filter (bandwidth = 0.033–0.125) was applied to the Kikai-SST_{coral}, Kikai-SST_{ERSST5}, CP-SST_{ERSST5}, and the NPGO Index before intercomparison. Although the number of previous VM studies is fewer than the NPGO studies, Wen et al. (2024) have applied an 11 year low-pass filter and then confirmed a robust correspondence between the conventional empirical orthogonal function-based VM index (Bond et al., 2003) and their newly proposed VMDI. In our study, based on spectral power analyses, we applied a 10–

30 year bandpass filter (bandwidth = 0.033–0.100) to the Kikai-SST_{coral} dataset and the VMDI before comparison. A 30 year running correlation was calculated to assess the temporal change in the relationship between time series at relatively low frequencies (i.e., using 8 year low-pass filtered data). Multi-taper spectral analysis and filtering were performed using Past software (v.5.2, Hammer et al., 2001). A trend change point was estimated using the "SiZer" package on R software (Chaudhuri and Marron, 1999; R Core Team, 2023; Sonderegger et al., 2009). Cross-wavelet coherence analysis was performed using the "biwavelet" package on R software (Gouhier et al., 2021; R Core Team, 2023).

The statistical significance of correlation coefficients, i.e., confidence levels (CL), was tested using the method described by Di Lorenzo et al. (2009) and Di Lorenzo et al. (2010), which accounts for the reduction in effective sample size (N_{eff}) due to filtering. The significance of the correlation coefficient was determined based on the probability distribution functions of the correlation coefficient of two randomly generated red noise time series. These two time series were randomly generated following the same autoregressive coefficients as those observed in the original two time series. The probability distributions are computed by generating 20,000 realisations of the correlation coefficient of two randomly generated red-noise time series. In all statistical reports, the correlation coefficient is denoted as *r*. The number of samples is reported as N_{eff} (for filtered data only) or *n* (for all other data). The significance of the statistical analyses is reported using *p*-values (for *t*-tests, Levene's test, field correlations, and cross-wavelet coherence analyses), confidence intervals (CI; for trend change point analyses), or CLs (for correlations of non-filtered and filtered time series). When the correlation coefficient *r* was not significant, it is denoted as *n.s.*

2.7 Reconstruction of NPGO–VM variability

Based on the results of intercomparison among NPGO, VM, and Kikai-SST_{coral} time series (Sect. 3.4), we reconstructed coral-based NPGO–VM variability over the past 217 years using Kikai-coral Sr/Ca_{summer} time series with the following equation (Eq. (1)).

$$\textit{Coral-based NPGO–VM variability} = \frac{(Sr/Ca - \overline{Sr/Ca_{1950-2014\ CE}})}{-\sigma}, \quad (1)$$

Where σ is the standard deviation of the time series for the period 1950–2014 CE. To isolate the low-frequency variability associated with NPGO and VM, high-frequency noise was removed by applying an 8 year low-pass filter (bandwidth = 0.000–0.125). We confirmed that both NPGO and VMDI time series exhibit distinct frequencies longer than an 8 year cycle (Fig. A9, 95 % CL for the NPGO Index; 90 % CL for the VMDI, see also Sect. 3.1). It is noted that, instead of Kikai-SST_{coral}, the Kikai-coral Sr/Ca_{summer} time series was used for reconstructing coral-based NPGO–VM variability in order to avoid the propagation of uncertainties introduced during the temperature conversion process.

3 Results

3.1 Significant periodicities in the NPGO and VM

We conducted spectral analyses of the NPGO Index dataset (Di Lorenzo et al., 2008) and the VMDI dataset (Wen et al., 2024) to identify their significant frequencies. For the NPGO Index, significant frequencies were detected at 9.8, 6.8–6.9, and 3.6 years at the 95 % CL, both with and without application of a 30 year high-pass filter (Figs. A9a and A9c). For the VMDI without filtering, distinct frequencies were identified at 51.2, 10.6, 3.7–3.9, and 2.4–2.5 years at the 90 % CL (Fig. A9b). After applying a 30 year high-pass filter, significant frequencies were detected at 12.4 and 10.6 years at the 95 % CL (Fig. A9d). These results indicate that the application of an 8 year low-pass filter (for the NPGO Index) or a 10 year low-pass filter (for the VMDI) effectively removes high-frequency variability. In addition, the 30 year high-pass filter effectively eliminates long-term trends or low-frequency components, such as global warming or variability associated with external forcing.

3.2 Kikai-coral Sr/Ca (this study)

3.2.1 Sr/Ca records from Core-1 to Core-3

Each coral Sr/Ca record obtained from the three coral cores revealed clear annual cycles (defined as from one winter peak to the subsequent winter peak) without interruptions (Fig. 2a; Table 1). No signatures of growth disturbances were observed, such as stress bands or growth cessations (Figs. 2a and A3). The modern coral, Core-1, covered the period from summer 1926 CE to the year of collection (2015 CE). The sub-fossil coral, Core-2, covered the period from autumn 1884 CE to spring 1931 CE, with a U–Th age of 1884 ± 1.5 CE (Table A2). Another sub-fossil coral, Core-3, covered the period from spring 1798 CE to winter 1886 CE, with U–Th ages of 1883 ± 2.5 CE and 1797 ± 2.6 CE (Table A2). There were overlapping periods between Core-1 and Core-2 (1926–1931 CE) and between Core-2 and Core-3 (1884–1886 CE). The accuracy of the age model was verified by comparing datasets for these overlapping periods. The overlapping skeletal Sr/Ca records correlated significantly at the 99 % CL (Core-1 and Core-2: $r = 0.79$, $n = 54$; Core-2 and Core-3: $r = 0.85$, $n = 18$; Fig. A6). In addition, no statistically significant differences were detected in mean Sr/Ca values for the overlapping periods among Core-1, Core-2, and Core-3, except for the mean of winter peaks between Core-1 and Core-2 (Fig. A6; Table A3). Furthermore, variance differences in summer and winter Sr/Ca values among cores were not statistically significant (summer Sr/Ca: p-value = 0.19; winter Sr/Ca: p-value = 0.72, Levene's test). These results confirm that the compiled coral Sr/Ca time series, i.e., Kika-coral Sr/Ca, provides a continuous record from 1798 to 2015 CE.

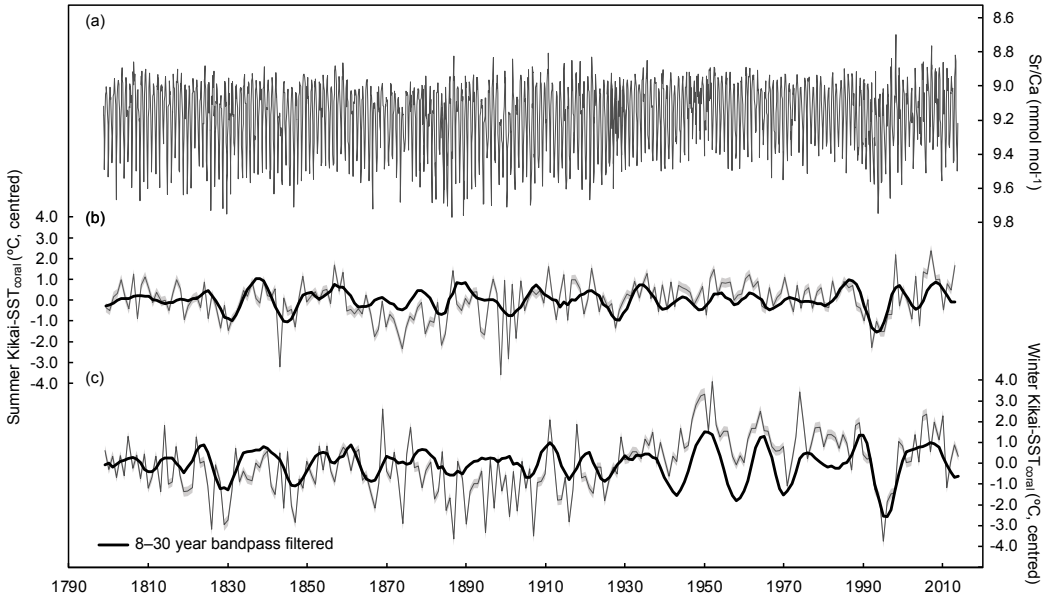

Figure 2. Kikai-coral Sr/Ca and Kikai-SST$_{coral}$ records.

The time series of (a) Kikai-coral Sr/Ca (mmol mol^{-1}), (b) Summer Kikai-SST$_{coral}$ (ºC, centred), and (c) Winter Kikai-SST$_{coral}$ (ºC, centred). See also Fig. A6, illustrating Kika-coral Sr/Ca for the overlapping periods (1926–1931 CE for between Core-1 and Core-2; 1884–1886 CE for between Core-2 and Core-3). The methodology for calculating Kikai-SST$_{coral}$ (figure panels b and c) converted from Kikai-coral Sr/Ca is described in Sect. 2.5. The uncertainty in temperature, represented by shading indicating 90 % CIs, was estimated using a Monte–Carlo approach (Watanabe and Pfeiffer, 2022).

Table 1. Summary of the Kikai-coral Sr/Ca record.

Core-1 is a modern *Porites* coral core collected in June 2015 CE. Core-2 and Core-3 are sub-fossil *Porites* coral cores. U–Th dating results for the sub-fossil cores are reported in Table A2. The overlapping intervals among the three cores are shown in Fig. A6. The number of annual cycles was determined based on Sr/Ca seasonal variability, counting one year as the period from one winter peak to the subsequent winter peak.

Specimens	Mean Sr/Ca (mmol mol^{-1})	Maximum Sr/Ca (mmol mol^{-1})	Minimum Sr/Ca (mmol mol^{-1})	Number of annual cycles	Period of Sr/Ca record
Core-1	9.14	9.79	8.67	89	1926–2015 CE
Core-2	9.22	9.81	8.79	46	1884–1931 CE
Core-3	9.19	9.79	8.84	87	1798–1886 CE

3.2.2 Summer, winter, and mean values of Kikai-coral Sr/Ca

To evaluate the characteristics of the Kikai-coral Sr/Ca record, we compared the summer, winter, and mean Sr/Ca values (Kikai-coral Sr/Ca$_{summer}$, Kikai-coral Sr/Ca$_{winter}$, and Kikai-coral Sr/Ca$_{annual\ mean}$; Sect. 2.5) with the annual mean values of the instrumental temperature derived from the grid cell covering the coral sampling site (Kikai-SST$_{ERSST5}$) for the period 1950–2014 CE. This comparison revealed that the summer, winter, and mean Sr/Ca values did not show significant correlations with

Kikai-SST$_{ERSST5}$ without filtering (for Kikai-coral Sr/Ca$_{summer}$: r = –0.12, n = 65, *n.s.*; Kikai-coral Sr/Ca$_{winter}$: r = 0.06, n = 65, *n.s.*; Kikai-coral Sr/Ca$_{annual\ mean}$: r = 0.03, n = 65, *n.s.*). In contrast, these coral Sr/Ca time series captured long-term temperature variability around Kikai Island when an 8–30 year bandpass filter was applied (for Kikai-coral Sr/Ca$_{summer}$: r = –0.69, N_{eff} = 8.02, significant at the 95 % CL; Kikai-coral Sr/Ca$_{winter}$: r = –0.67, N_{eff} = 9.29, significant at the 99 % CL; Kikai-coral Sr/Ca$_{annual\ mean}$: r = –0.78, N_{eff} = 7.58, significant at the 99 % CL; Fig. A10).

3.2.3 Comparison of coral Sr/Ca records from Kikai Island

On Kikai Island, coral Sr/Ca records have been published by Kawakubo et al. (2017) and Morimoto et al. (2007). We compared our Kikai-coral Sr/Ca record with these previously published records to assess consistency and differences.

In a comparison between our Kikai-coral Sr/Ca record and the previously published record by Kawakubo et al. (2017) for the period 1950–2008 CE, we found a correlation between Kikai-coral Sr/Ca$_{summer}$ and the previously published summer values only at the 90 % CL (r = 0.50, N_{eff} = 8.22, 8–30 year bandpass filtered; Fig. A10a). In contrast, no significant correlation was observed between Kikai-coral Sr/Ca$_{winter}$ and the previously published winter values (r = –0.35, N_{eff} = 7.14, *n.s.*, 8–30 year bandpass filtered; Fig. A10b). Additionally, unlike the results from our coral record (Sect. 3.2.2), neither the summer nor the winter values from the previously published record (Kawakubo et al., 2017) showed a significant correlation with the instrumental temperature record (Kikai-SST$_{ERSST5}$) (summer values: r = –0.24, N_{eff} = 8.49, *n.s.*, 8–30 year bandpass filtered; Fig. A10a, winter values: r = –0.23, N_{eff} = 11.10, *n.s.*, 8–30 year bandpass filtered; Fig. A10b).

Morimoto et al. (2007) documented a short-term coral Sr/Ca record from Kikai Island. Its record length (< 6 years) is insufficient to assess past interannual-to-decadal-scale variability. Although the absolute Sr/Ca values differed between our Kikai-coral Sr/Ca record and that of Morimoto et al. (2007), likely due to the intercolonial differences (Corrège, 2006), the seasonal ranges of the records were largely consistent (Table A4).

3.3 Kikai-SST$_{coral}$ (this study)

As demonstrated in Sect. 3.2.2, both the Kikai-coral Sr/Ca$_{summer}$ and Kikai-coral Sr/Ca$_{winter}$ time series have the potential to reconstruct long-term temperature variability around Kikai Island. Accordingly, we converted these time series into temperature values (ºC, Summer Kikai-SST$_{coral}$ and Winter Kikai-SST$_{coral}$; Sect. 2.5). The time series of Summer and Winter Kikai-SST$_{coral}$ are shown in Figs. 2b and 2c. The spectral power analyses revealed significant periodicities both with and without 30 year high-pass filter (Fig. A11). In particular, significant frequencies at 16.4 and 15.2 years for Summer Kikai-SST$_{coral}$ (at the 95 % CL, Fig. A11c) and at 18.2, 12.8, 9.3, and 8.3 years for Winter Kikai-SST$_{coral}$ (at the 95 % CL, Fig. A11d) fell within the range of filters applied in this study (Sect. 2.6).

Significant relationships were confirmed between Summer Kikai-SST$_{coral}$ and Kikai-SST$_{ERSST5}$, and between Winter Kikai-SST$_{coral}$ and Kikai-SST$_{ERSST5}$, at the 95 % CL from 1950 to 2014 CE (8–30 year bandpass filtered; Figs. 3a, 3c, and 3e; Table 2a). However, for the longer period (1900–2014 CE), no significant correlations were observed (8–30 year bandpass filtered; Figs. 3a, 3c, and 3e; Table 2b). Moreover, Summer Kikai-SST$_{coral}$ time series matched the SST time series in the CP (CP-

SST_{ERSST5}). A significant negative correlation was observed between the two time series at the 99 % CL from 1950 to 2014 CE (8–30 year bandpass filtered; Figs. 3b and 3d; Table 2a). Even over the longer period from 1900 to 2014 CE, the significant relationship was maintained (8–30 year bandpass filtered; Figs. 3b and 3d; Table 2b). While the Winter Kikai-SST_{coral} time series showed a significant relationship with CP-SST_{ERSST5} at the 95 % CL from 1950 to 2014 CE (8–30 year bandpass filtered; Figs. 3b and 3f; Table 2a), but only at the 90 % CL from 1900 to 2014 CE (8–30 year bandpass filtered; Figs. 3b and 3f; Table 2b).

A significant correlation was also observed with the previously published coral-based temperature record from Palmyra, located in the central tropical Pacific, dating back to 1887 CE (referred to as "Palmyra-SST_{coral}") (Nurhati et al., 2011). Summer Kikai-SST_{coral} correlated with Palmyra-SST_{coral} at the 95 % CL (8–30 year bandpass filtered; Figs. A12a and A12c; Table 2c), whereas no significant relationship was obtained for Winter Kikai-SST_{coral} (8–30 year bandpass filtered; Figs. A12a and A12e; Table 2c). In addition, no significant correlation was observed with the previously published coral $\delta^{18}O$ record from Clarion Island, located in the northeastern Pacific (NEP), dating back to 1820 CE (referred to as "Clarion-$\delta^{18}O_{coral}$") (Sanchez et al., 2016) (8–30 year bandpass filtered; Fig. A12b, A12d, and A12f; Table 2c).

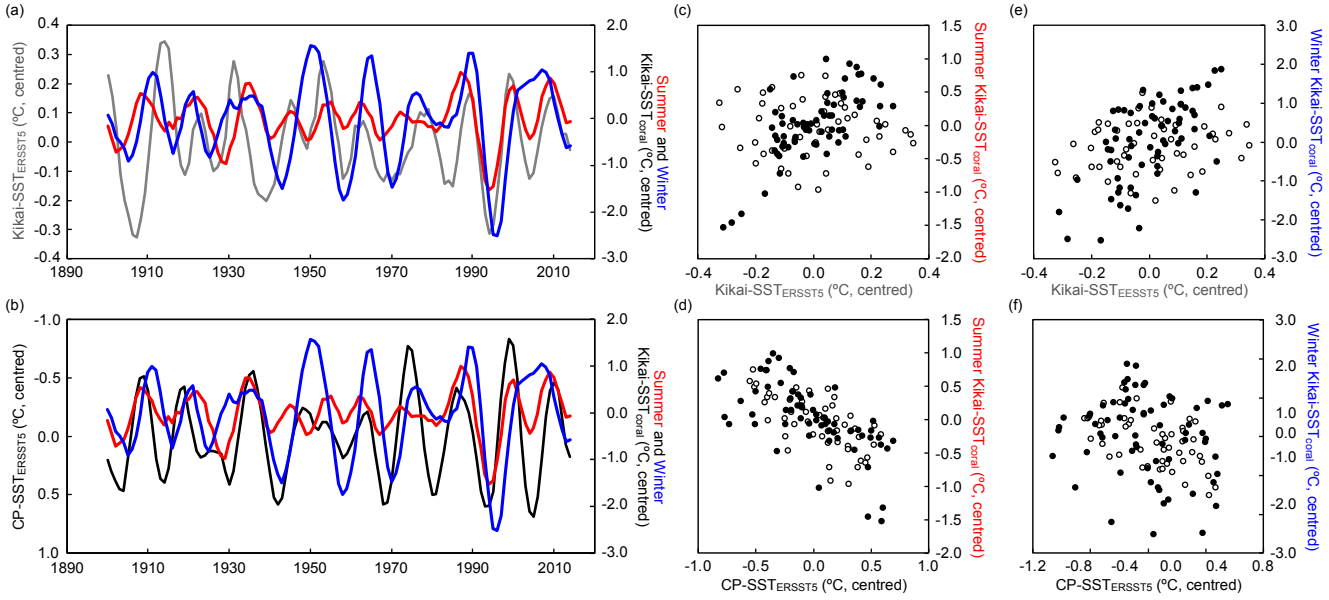

Figure 3. Time series comparisons of coral-based temperature and SST datasets from 1900 to 2014 CE.

Comparison of (a) Summer (in red) and Winter Kikai-SST_{coral} (in blue) and annual mean Kikai-SST_{ERSST5} (in grey, Huang et al., 2017); (b) Summer (in red) and Winter Kikai-SST_{coral} (in blue) and annual mean CP-SST_{ERSST5} (in black). An 8–30 year bandpass filter was applied to all time series. (c)(d)(e)(f) Scatter plots corresponding to (a) and (b). Open-circle plots are data for the period 1900–1949 CE. Closed-circle plots are data for the period 1950–2014 CE.

Table 2. Correlation among Kikai-SST$_{coral}$ (this study), the instrumental SST record (ERSST5) around Kikai Island and in the CP, and previously published coral records.

Correlation among Summer or Winter Kikai-SST$_{coral}$ and the instrumental SST record (ERSST5; Huang et al., 2017) for the periods (a) from 1950 to 2014 CE and (b) from 1900 to 2014 CE. (c) Correlation among Summer or Winter Kikai-SST$_{coral}$ and annual mean values of the previously published coral records. An 8–30 year bandpass filter was applied to all time series prior to calculating correlations.

(a) Comparison of seasonal Kikai-SST$_{coral}$ dataset and the annual mean instrumental SST record, for the period 1950–2014 CE

Pair of correlation analysis	Period	*r*	significance	N_{eff}
Summer Kikai-SST$_{coral}$ versus Kikai-SST$_{ERSST5}$	1950–2014 CE	0.69	95 % CL	7.94
Summer Kikai-SST$_{coral}$ versus CP-SST$_{ERSST5}$	1950–2014 CE	–0.66	99 % CL	6.71
Winter Kikai-SST$_{coral}$ versus Kikai-SST$_{ERSST5}$	1950–2014 CE	0.68	95 % CL	8.94
Winter Kikai-SST$_{coral}$ versus CP-SST$_{ERSST5}$	1950–2014 CE	–0.18	*n.s.*	6.02

(b) Comparison of seasonal Kikai-SST$_{coral}$ dataset and the annual mean instrumental SST record, for the period 1900–2014 CE

Pair of correlation analysis	Period	*r*	significance	N_{eff}
Summer Kikai-SST$_{coral}$ versus Kikai-SST$_{ERSST5}$	1900–2014 CE	0.34	*n.s.*	15.26
Summer Kikai-SST$_{coral}$ versus CP-SST$_{ERSST5}$	1900–2014 CE	–0.65	95 % CL	9.80
Winter Kikai-SST$_{coral}$ versus Kikai-SST$_{ERSST5}$	1900–2014 CE	0.41	90 % CL	18.74
Winter Kikai-SST$_{coral}$ versus CP-SST$_{ERSST5}$	1900–2014 CE	–0.28	*n.s.*	10.96

(c) Comparison of seasonal Kikai-SST$_{coral}$ dataset and the previously published coral records

Pair of correlation analysis	Period	*r*	significance	N_{eff}
Summer Kikai-SST$_{coral}$ versus Palmyra-SST$_{coral}$	1887–1997 CE	–0.56	95 % CL	12.73
Summer Kikai-SST$_{coral}$ versus Clarion-$\delta^{18}O_{coral}$	1820–1997 CE	0.30	*n.s.*	21.51
Winter Kikai-SST$_{coral}$ versus Palmyra-SST$_{coral}$	1887–1997 CE	–0.16	*n.s.*	11.91
Winter Kikai-SST$_{coral}$ versus Clarion-$\delta^{18}O_{coral}$	1820–1997 CE	0.23	*n.s.*	26.39

3.4 Comparison among the NPGO Index, the VMDI, and Kikai-SST$_{coral}$

Field correlation patterns between Kikai-SST$_{coral}$ and instrumental SST or SSHa revealed spatial structures resembling those of the VM and NPGO mode (compare Fig. 1 with Fig. 4), particularly for Summer Kikai-SST$_{coral}$. In particular, the field correlation pattern between Summer Kikai-SST$_{coral}$ and ERSST5 for the period 1950–2014 CE (Fig. 4a) was consistent with the documented distribution of the NPGO pattern in Pacific SSTa (refer to Fig. 4b of Di Lorenzo et al., 2008) and VM-like temperature distribution in the North Pacific (refer to Fig. 1a of Wen et al., 2024). When extended back to 1900 CE (Fig. 4c), the field correlation pattern still showed an NPGO-like structure in the Pacific SSTa field. Compared to the period 1950–2014 CE (Fig. 4a), the correlation coefficients for the longer period 1900–2014 CE (Fig. 4c) were generally lower, likely reflecting reduced quality of the ERSST5 dataset prior to 1950 CE, owing to higher uncertainty or sparseness (see Sect 4.1). These results suggest that our coral record captures temperature signals associated with NPGO and VM and may thus serve as a proxy for reconstructing NPGO- and VM-related temperature variability during periods when instrumental observations are sparse or uncertain, and potentially even further back into the pre-instrumental period.

Notably, Summer Kikai-SST$_{coral}$ significantly correlated with the annual mean NPGO Index from 1950 to 2014 CE at the 99 % CL (8–30 year bandpass filtered; Figs. 5a and 5e; Table 3a). Winter Kikai-SST$_{coral}$ also appears to reflect NPGO variability, although the correlation between them for the same period was significant only at the 90 % CL (8–30 year bandpass filtered; Figs. 5b and 5f; Table 3a). Similarly, Summer Kikai-SST$_{coral}$ significantly correlated with the annual mean VMDI from 1950 to 2014 CE at the 99 % CL (10–30 year bandpass filtered; Figs. 5c and 5g; Table 3b), whereas Winter Kikai-SST$_{coral}$ showed

a significant relationship with the VMDI only at the 90 % CL (10–30 year bandpass filtered; Figs. 5d and 5h; Table 3b). For the longer period (from 1900 to 2014 CE), neither Summer Kikai-SST_{coral} nor Winter Kikai-SST_{coral} exhibited a significant relationship with the VMDI (Table 3b).

As seen in the comparison between the NPGO Index and the VMDI (Fig. A1), the two time series generally matched, although a short interval of reduced synchronicity was observed between the late 1960s and the 1970s. During this period, Summer Kikai-SST_{coral} closely tracked the annual mean VMDI (Fig. 5c), whereas it did not track the annual mean NPGO Index (Fig. 5a). Based on the overall similarity between the NPGO Index and VMDI (Figs. 1 and A1) and the robust relationship between Summer Kikai-SST_{coral} and NPGO or VM variability, Summer Kikai-SST_{coral} has the potential to reconstruct the oceanic expression of the dynamically linked mode between NPGO and VM and its long-term variability (i.e., NPGO–VM variability).

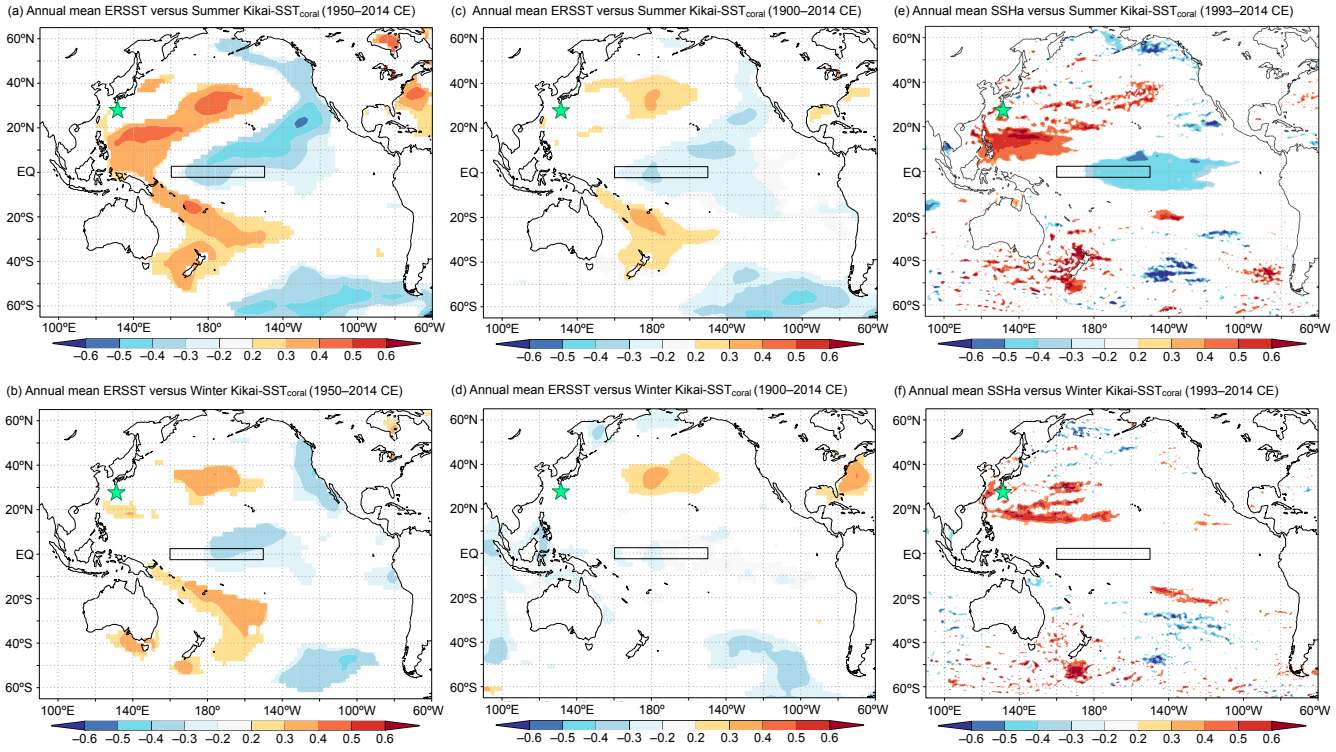

Figure 4. Spatial distribution of the NPGO and VM pattern shown in SST and SSH fields.

(a) Field correlation map between Summer Kikai-SST_{coral} (this study) and the annual mean SST time series (ERSST5; Huang et al., 2017) from 1950 to 2014 CE. (b) Field correlation map between Winter Kikai-SST_{coral} and the annual mean SST time series (ERSST5; Huang et al., 2017) from 1950 to 2014 CE. (c) Same as (a), but covering the period from 1900 to 2014 CE. (d) Same as (b), but covering the period from 1900 to 2014 CE. (e) Field correlation map between Summer Kikai-SST_{coral} and the annual mean SSHa time series from 1993 to 2014 CE. (f) Field correlation map between Winter Kikai-SST_{coral} and the annual mean SSHa time series from 1993 to 2014 CE. All correlations are computed using detrended data. Only correlations with *p*-values < 0.1 are colour-coded. The original figures in each panel were computed using the web application KNMI Climate Explorer (https://climexp.knmi.nl/) and plotted using GrADS (v2.2.1). The location of the coral sampling site (Kikai Island, Kagoshima, Japan) is marked by a star. The black box indicates the CP region (5° S–5° N, 160° E–150° W).

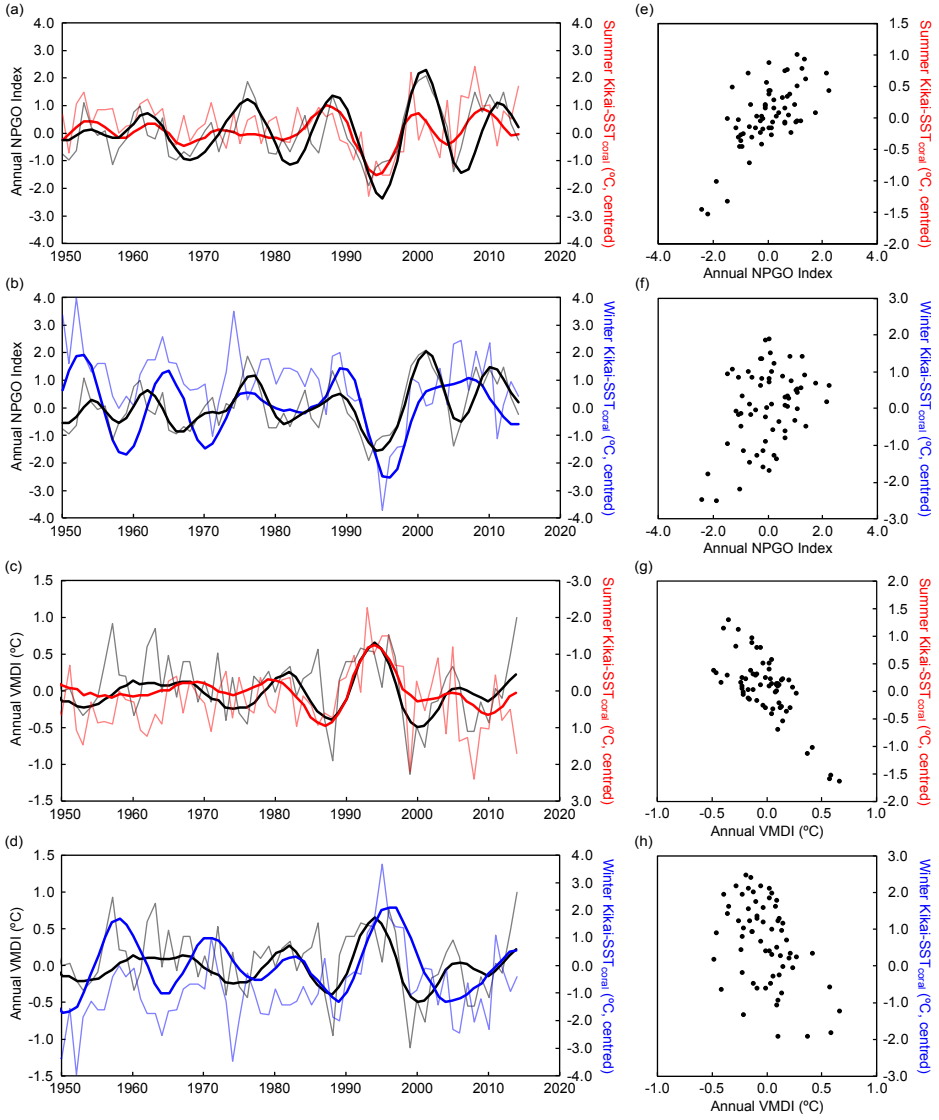

Figure 5. Comparison of the annual mean NPGO Index, annual mean VMDI, and Kikai-SST$_{coral}$ (1950–2014 CE).

Time series of (a) the annual mean NPGO Index (thin black line, Di Lorenzo et al., 2008) and Summer Kikai-SST$_{coral}$ (thin red line); (b) the annual mean NPGO Index (thin black line) and Winter Kikai-SST$_{coral}$ (thin blue line); (c) the annual mean Victoria Mode Dipole Index (thin black line, VMDI, Wen et al., 2024, calculated using ERSST5) and Summer Kikai-SST$_{coral}$ (thin red line); (d) the VMDI (thin black line) and Winter Kikai-SST$_{coral}$ (thin blue line). Bold lines in panels (a) and (b) represent the 8–30 year bandpass filtered time series. Bold lines in panels (c) and (d) represent the 10–30 year bandpass filtered time series. (e)(f)(g)(h) Scatter plot corresponding to (a)(b)(c)(d), for the bandpass filtered dataset.

Table 3. Correlation among Kikai-SST$_{coral}$ (this study), the NPGO Index, and the VMDI.

Correlation among Summer or Winter Kikai-SST$_{coral}$ and (a) the annual mean NPGO Index (Di Lorenzo et al., 2008), (b) the annual mean Victoria Mode Dipole Index (VMDI, Wen et al., 2024, calculated using ERSST5). Prior to calculating correlations, (a) an 8–30 year bandpass filter and (b) a 10–30 year bandpass filter were applied to the time series.

(a) Comparison of the seasonal Kikai-SST$_{coral}$ dataset and the annual mean NPGO Index

Pair of correlation analysis	Period	*r*	significance	N_{eff}
Summer Kikai-SST$_{coral}$ versus NPGO Index	1950–2014 CE	0.67	99 % CL	7.27
Winter Kikai-SST$_{coral}$ versus NPGO Index	1950–2014 CE	0.45	90 % CL	5.80

(b) Comparison of the seasonal Kikai-SST$_{coral}$ dataset and the annual mean VMDI

Pair of correlation analysis	Period	*r*	significance	N_{eff}
Summer Kikai-SST$_{coral}$ versus VMDI	1950–2014 CE	–0.74	99 % CL	7.90
Winter Kikai-SST$_{coral}$ versus VMDI	1950–2014 CE	–0.45	90 % CL	7.40
Summer Kikai-SST$_{coral}$ versus VMDI	1900–2014 CE	–0.31	*n.s.*	14.97
Winter Kikai-SST$_{coral}$ versus VMDI	1900–2014 CE	–0.28	*n.s.*	12.93

4. Discussions

4.1 Potential ability of corals derived from Kikai Island to reconstruct NPGO–VM variabilities

4.1.1 Ocean–atmosphere bridge over the Central and Northwest Pacific

The VM likely explains the observed linkage between the NWP and CP by acting as an "oceanic bridge" that connects the NPO and CP-centred ENSO phenomena (Ding et al., 2015; Qi and Mao, 2022). In addition, temperature variability in the CP serves as a driving force for large-scale atmospheric circulation in the central North Pacific (i.e., NPO), which in turn feeds back onto ocean dynamics and excites NPGO responses. This feedback connecting the NPGO and temperature variability in the CP has been referred to as an "atmospheric bridge" (Alexander et al., 2002; Di Lorenzo et al., 2010). Given these interrelationships between oceanic and atmospheric modes, the temperature variability observed in the NWP, including at our study site, is likely influenced by NPGO–VM-related temperature variations propagated from the CP via the "ocean–atmosphere bridge," particularly on long-term temporal scales.

Indeed, the Summer Kikai-SST$_{coral}$ time series implied the effects of the "ocean–atmosphere bridge" connecting the NWP and CP. This is evidenced by its significant correlations with both CP-SST$_{ERSST5}$ (Figs. 3b and 3d; Tables 2a and 2b) and Palmyra-SST$_{coral}$ (Figs. A12a and A12c; Table 2c). This consistency indicates a robust climatic linkage between our NWP coral-based temperature record and the temperature variability in the CP. Between 1950 and 2014 CE, CP-SST$_{ERSST5}$ significantly correlated with Kikai-SST$_{ERSST5}$ at the 95 % CL (r = –0.43, N_{eff} = 6.34, 8–30 year bandpass filtered; Fig. A13), supporting a temperature linkage between the NWP and CP regions. In contrast, no significant correlation was observed over the longer period from 1900 to 2014 CE (r = –0.29, N_{eff} = 17.72, *n.s.*, 8–30 year bandpass filtered; Fig. A13), which is consistent with the absence of a significant correlation between Summer or Winter Kikai-SST$_{coral}$ and Kikai-SST$_{ERSST5}$ over the same interval (Sect. 3.3; Figs. 3a, 3c, and 3e; Table 2b). This lack of correlations may be attributed to the reduced quality of instrumental SST datasets prior to 1950 CE (Thompson et al., 2008; Pfeiffer et al., 2017) for the grid covering Kikai Island (i.e, Kikai-

SST_{ERSST5}), which can introduce statistical biases in estimates of long-term temperature variability (Sippel et al., 2024). Such limitations complicate the reconstruction of NPGO–VM-related temperature variability and its regional influence prior to 1950 CE. A precise, high-temporal-resolved temperature proxy record, such as a coral Sr/Ca-based temperature reconstruction, can address this limitation because it is independent of lower-quality instrumental SST records (Pfeiffer et al., 2017). In particular, coral-based temperature records derived from Kikai Island in the NWP have the capacity to reconstruct NPGO and VM variabilities (Sect. 3.4). Moreover, cross-wavelet coherence analysis (Fig. A14) revealed that our coral records, especially Summer Kikai-SST_{coral} and the NPO variability, were coherent at interannual-to-decadal timescales throughout the period 1950–2014 CE. Taken together, the significant relationships between Kikai-SST_{corals} and CP-SST_{ERSST5} variability or NPO variability support the existence of the "ocean–atmosphere bridge," and agree with NPGO-mode-centred Pacific decadal dynamics and teleconnections, as proposed by Di Lorenzo et al. (2013) (see their Fig. 1).

4.1.2 Potential factors underlying differences in response to the NPGO–VM-related temperature variations recorded in coral geochemical records from Kikai Island

Consistent with our results (Sect. 3.4), the previously published long-term coral Sr/Ca record from Kikai Island (Kawakubo et al., 2017) also appears to capture NPGO–VM-related temperature variations propagated from the CP via the "ocean–atmosphere bridge." Our coral records showed significant correlations with both NPGO and VMDI, whereas only the summer values reported by Kawakubo et al. (2017) exhibited a significant relationship with the annual mean VMDI from 1950 to 2009 CE at the 99 % CL (r = 0.65, N_{eff} = 6.34, 10–30 year bandpass filtered); no significant relationship was identified with the NPGO Index. Thus, although the records were derived from the same region, their responses to NPGO–VM-related temperature variations differ. This difference is further supported by the relatively weak correlation between our Kikai-coral Sr/Ca record and that of Kawakubo et al. (2017) (Sect. 3.2.3). Several factors may contribute to these differences, including local environmental conditions associated with the coral core collection sites. The coral core collection sites in the previous studies by Kawakubo et al. (2017) and Morimoto et al. (2007) are located offshore of Arakizaki Point, southwest of Kikai Island (Fig. A2a). On the other hand, our coral cores were collected from Shiomichi Bay, northeast of Kikai Island (Fig. A2a). Kikai Island is a small island with a perimeter of 48.6 km; however, its coastline and surrounding coral reef environments exhibit substantial spatial heterogeneity. The offshore of Arakizaki Point is an open ocean, and is geomorphologically characterised by a reef slope with widely developed coral or algal cover (Figs. A2c and A2e), whereas Shiomichi Bay is a semi-closed bay, and is characterised by an outer-reef flat with less-developed coral or algal cover (Figs. A2b and A2d). Such environmental differences at coral core collection sites can influence coral geochemical signals and may explain the non-significant relationship observed in the long-term comparison analysis between our Kikai-coral Sr/Ca record and that of Kawakubo et al. (2017) (Sect. 3.2.3).

In addition to local environmental factors, differences in analytical methods and analytical precision may also affect the resulting datasets. These methodological differences are particularly significant when reconstructing paleoclimate/temperature variability, such as NPGO–VM-related temperature variability. Our coral record provides higher analytical precision compared

to the previously published records. This advantage was achieved through the use of solution ICP-OES analysis (Watanabe et al., 2020). On the other hand, the previously published long-term Sr/Ca record from Kikai Island (Kawakubo et al., 2017) was obtained using laser ablation Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Kawakubo et al., 2014). The reported analytical uncertainty was 0.3 %RSD (Kawakubo et al., 2017). It was equivalent to 0.4 ºC when accounting for both the analytical uncertainty and the uncertainty of the Sr/Ca-temperature calibration slopes, as calculated following Watanabe and Pfeiffer (2022). This analytical precision (0.3 %RSD) is lower than that of our method (0.1 %RSD). Such differences in analytical precision can lead to discrepancies in the expression of coral Sr/Ca signals associated with NPGO–VM-related temperature variability across different timescales. Another coral Sr/Ca record from Kikai Island (Morimoto et al., 2007) was obtained using thermal ionisation mass spectrometry (TIMS) with the isotope dilution method (Alibert and McCulloch, 1997), which offers precision comparable to that of our analytical method. The reported analytical uncertainty was 0.1 %RSD (1σ, Morimoto et al., 2007). It was equivalent to 0.14 ºC when accounting for both the analytical uncertainty and the uncertainty of the Sr/Ca-temperature calibration slopes, as calculated following Watanabe and Pfeiffer (2022). However, because the record is less than 6 years long, it is insufficient to evaluate coral Sr/Ca responses to NPGO–VM-related temperature variability or to meaningfully compare with our long-term record.

4.1.3 Growth effects on seasonal differences in the coral Sr/Ca record

Through the intercomparison analyses (Sects. 3.2, 3.3, and 3.4), we found that the winter component of the coral geochemical proxy data from Kikai Island does not accurately reflect long-term temperature variability, unlike the summer component. Seasonal variability in coral growth rates likely contributes to this discrepancy. Generally, warmer SSTs during the summer season promote faster coral growth, while cooler SSTs during the winter season lead to slower growth. Such seasonal growth-rate differences result in more data points being recorded during summer and fewer during winter (Barnes et al., 1995). This bias would be more distinct in coral geochemical proxy data from the subtropics than from the tropics due to a larger seasonal temperature amplitude. As illustrated in the histogram of Kikai-coral Sr/Ca values (Fig. A15), there were more data points in summer and mid-season, consistent with previous observations for subtropical corals (Kawakubo et al., 2014, Kikai Island) and temperate corals (Fallon et al., 1999, Shikoku region, Japan). Both our results and Kawakubo et al. (2014) suggest that biweekly-to-monthly resolved geochemical records from *Porites* corals at Kikai Island may be biased toward summer values. To better capture the winter signal in coral geochemical proxies from Kikai Island, a combined approach may be required, incorporating high-spatial-resolution techniques such as laser ablation (e.g., Kawakubo et al., 2014) alongside the high-precision analytical methods employed in this study.

Our results suggest that Summer Kikai-SST_{coral} has a strong, consistent relationship with instrumental SST datasets, the NPGO Index, and the VMDI (Sects. 3.3 and 3.4). From a theoretical perspective, because the NPGO and VM are considered to be dominant during boreal winter and spring/early summer, not only the Summer Kikai-SST_{coral} but also the Winter Kikai-SST_{coral} would be expected to capture signals of NPGO–VM-related temperature variability. However, Winter Kikai-SST_{coral} exhibited a weaker relationship with the VMDI than Summer Kikai-SST_{coral}. Similarly, weak or non-significant relationships were

identified in comparisons with instrumental SST datasets. These discrepancies observed between the summer and winter components would be explained by a seasonal growth bias in the Kikai-coral Sr/Ca dataset. The Kikai-coral Sr/Ca_{summer} dataset is minimally affected by seasonal growth bias and more accurately reflects long-term SST variability compared to the Kikai-coral Sr/Ca_{winter} dataset. The Kikai-coral $Sr/Ca_{annual\ mean}$ dataset is also subject to bias because the annual mean incorporates both summer and winter values. Consequently, we conclude that Kikai-coral Sr/Ca_{summer} is the most appropriate dataset for reconstructing NPGO–VM-related temperature variability in this study.

4.2 Coral-based NPGO–VM variability reconstruction back to the 19th century

We reconstructed coral-based NPGO–VM variability over the past 217 years using the 8 year low-pass filtered dataset of Kikai-coral Sr/Ca_{summer}, applying Eq. (1) (see also Sect. 2.7). The resulting reconstruction extends back to the early 19th century, providing insight into long-term NPGO–VM variability prior to the instrumental period.

4.2.1. NPGO-VM variability in the 19th and 20th centuries

The time series of reconstructed NPGO–VM variability is shown in Fig. 6a. Prior to the 1850s, the record was characterised by alternating negative and positive modes. It is well-known that several major volcanic eruptions occurred between the 1800s and 1830s (the late phase of the Little Ice Age), and that these eruptions caused multi-year cooling following each event (Brönnimann et al., 2019). Both the Kika-coral Sr/Ca record and coral-based NPGO–VM variability exhibited a cooling phase during the late 1820s to the early 1830s, coincident with this period of frequent volcanic eruptions. Although volcanic forcing cannot be entirely excluded as a contributing factor, its overall influence appears limited, given the relatively modest amplitude of the cooling signal. During the 1860s–1900s, a pronounced negative-NPGO/positive-VM phase (coral-based NPGO–VM variability < -1.0, corresponding to cool-temperature in the NWP) was observed. This interval occurred well after the late phase of the Little Ice Age and after the period of major volcanic eruptions, suggesting that it was unlikely to have been driven primarily by volcanic forcing. Notably, this strong negative-NPGO/positive-VM phase aligns well with the previously reported low-temperature conditions recorded in coral archives from Kikai Island (Kawakubo et al., 2017) and southern Taiwan (Ramos et al., 2020). Kawakubo et al. (2017) further reported a closely concurrent reduction in atmospheric variability, inferred from the Gibraltar/Reykjavik North Atlantic Oscillation Index (Vinther et al., 2003), from 1870 to 1900 CE, which may be linked to this cool temperature period. However, further investigations are required to elucidate the connection between reduced atmospheric variability and NPGO or VM dynamics during that time. Furthermore, this pronounced negative-NPGO/positive-VM phase may be related to the late onset of the warming trend in the NWP. We identified a trend change point at 1873 CE (95 % CI: 1844–1877 CE, see diamond symbol in Fig. 6a), indicating that the onset of the warming trend in the NWP might be later than previous estimates for other ocean basins and the Northern Hemisphere (estimated using "Western Pacific Ocean" archive; Abram et al., 2016). The previously used "Western Pacific Ocean" archive primarily comprises data from the southern and central western Pacific; therefore, it may be insufficient to capture temperature trends specifically in the NWP. Our Kikai-coral Sr/Ca record would complement this spatial data gap. Since a similar cool-temperature phase was also reported in other

NWP coral records (Kawakubo et al., 2017; Ramos et al., 2020), the delayed onset of warming may be a regional feature specific to the NWP. However, long-term temperature reconstructions in this region remain limited, and further studies are necessary to more accurately determine the onset of warming. Following the negative-NPGO/positive-VM phase during the 1860s–1900s, the reconstructed NPGO–VM variability shows alternating negative and positive modes through the early 20th century. In the late 20th century, positive-NPGO/negative-VM phases occurred intermittently; however, the overall amplitude of variability was relatively small (within ±1.0 coral-based NPGO/VM variability). This suggests a comparatively stable regime of NPGO–VM-related variability, similar to that observed prior to the 1820s. In contrast, a prominent negative-NPGO/positive-VM phase (coral-based NPGO–VM variability < –1.0, corresponding to cool-temperature in the NWP) was again observed in the 1990s, with an amplitude comparable to the prolonged negative phase that occurred between the 1860s and the 1900s.

4.2.2 NPGO-VM variability in the 21st century

Since the early 2000s, the reconstructed NPGO–VM variability has shifted toward a distinct positive-NPGO/negative-VM phase (coral-based NPGO–VM variability > 1.0, corresponding to warm-temperature in the NWP) (Fig. 6a). This shift is likely related to the higher frequency of climate variability in the CP in recent decades (Yeh et al., 2011). Several previous studies have proposed that the higher frequency of climate variability in the CP due to anthropogenic warming may enhance NPGO variability and strengthen the linkage between them (e.g., Dong et al., 2022). In addition, the occurrence ratio of CP-centred ENSO compared to EP-centred ENSO (i.e., the CP/EP event ratio) has increased in response to current global warming and is projected to continue increasing under future warming scenarios (Freund et al., 2019; Shen and Yu, 2023; Yeh et al., 2009). It has also been revealed that the NPO/NPGO mode has become more dominant in the North Pacific rather than the Aleutian Low/PDO mode in recent decades, reflecting the increasing prevalence of CP-centred ENSO events in the tropical Pacific (Di Lorenzo et al., 2010; Yeh et al., 2011). Furthermore, VM variability is expected to become more pronounced in association with amplified temperature variability in the CP under an anthropogenic warming scenario with rapid greenhouse gas emission (RCP8.5 scenario) (Ji et al., 2024). Taken together, these findings suggest that the positive-NPGO/negative-VM phase observed in the early 21st century may reflect an emerging regime of NPGO-VM variability driven, at least in part, by anthropogenic climate forcing.

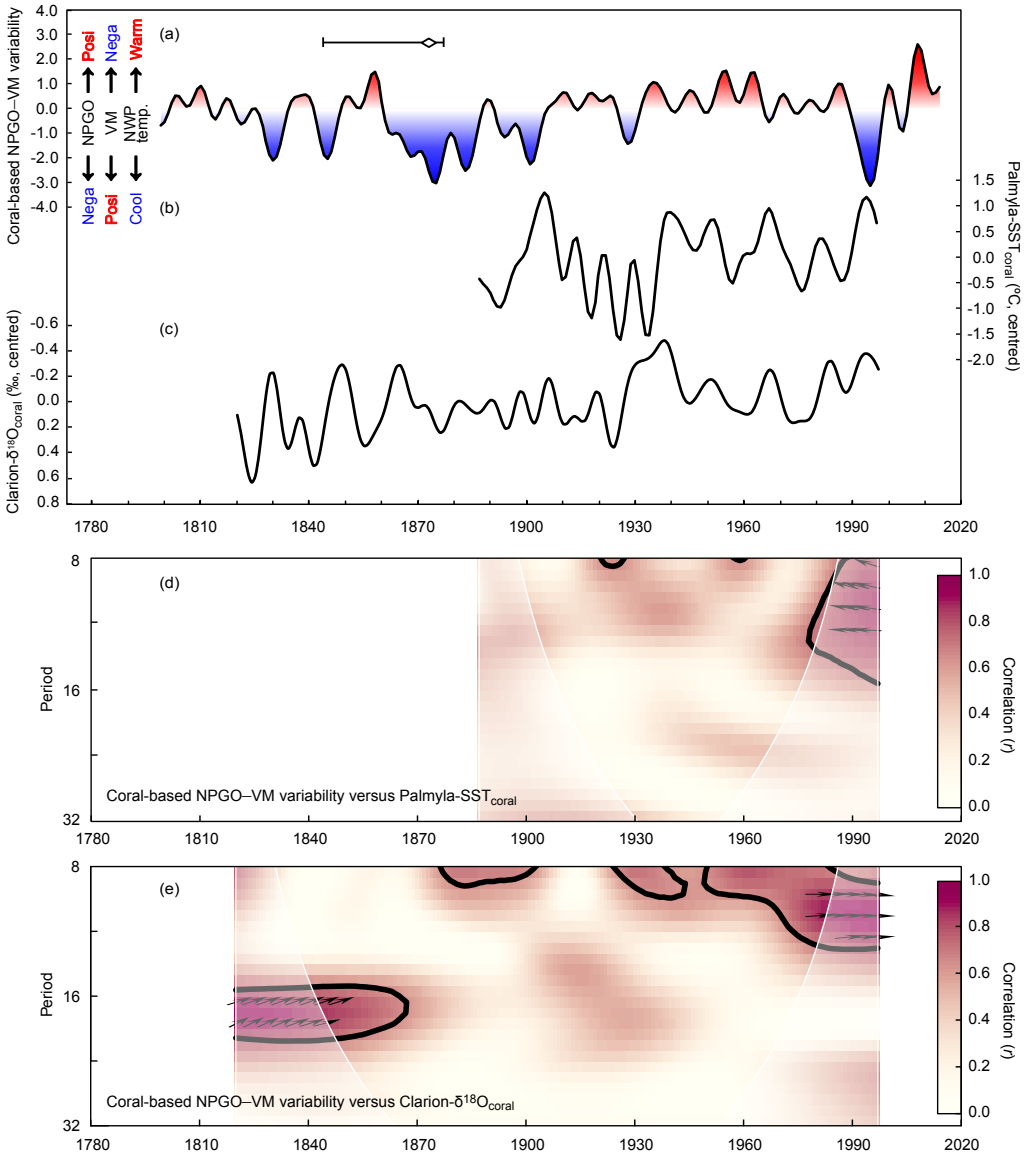

Figure 6. Reconstructed NPGO–VM variability extending back to 1798 CE.

(a) Coral-based NPGO–VM variability. An 8 year low-pass filter was applied to the datasets before calculation. Blue-coloured portions indicate negative phases of NPGO or positive phases of VM (< 0, cool-temperature in the NWP), while red-coloured portions indicate positive phases of NPGO or negative phases of VM (> 0, warm-temperature in the NWP). The diamond symbol denotes a detected trend change point, determined using the "SiZer" package (version 0.1-8) on R software (Chaudhuri and Marron, 1999; R Core Team, 2023; Sonderegger et al., 2009). The horizontal error bar represents the estimated uncertainty associated with the trend change point. (b) Palmyra-SST$_{coral}$ dataset reported by Nurhati et al. (2011) (8 year low-pass filtered). (c) Clarion-δ^{18}O$_{coral}$ dataset reported by Sanchez et al. (2016) (8 year low-pass filtered). (d) Cross-wavelet coherence between time series (a) and (b) from 1887 to 1997 CE. Regions of significant coherence (*p*-values < 0.1) are outlined by solid contours. Arrows indicate the phase relationship. The cross-wavelet coherence was computed using the "biwavelet" package (version 0.20.21) on R software (Gouhier et al., 2021; R Core Team, 2023). (e) Same as (d), but between time series (a) and (c) from 1820 to 1997 CE.

4.3 Contribution of NPGO–VM in the North Pacific or NWP

We found a significant historical correlation between the CP-SST_{ERSST5} and coral-based NPGO–VM variability lasting from the early 20th century until 2014, with the exception of the period from the early 1970s to the 1980s (Fig. 7a). This exceptional period corresponds to a lack of synchronicity between the SST in the North Pacific/NWP and the NPGO Index (from the late 1960s to the 1980s; Fig. A1 for VMDI versus NPGO Index; Fig. 5a for Summer Kikai-SST_{coral} versus NPGO Index). A previous study has indicated a regime shift related to the NPGO in 1988/1989 CE (Yeh et al., 2011); however, there is no evidence of such a regime shift or anomalous variation in the NPGO during the late 1960s–1980s. One possible explanation for the lack of synchronicity is the dominance of VM-related variability during that period. The comparison between Summer Kikai-SST_{coral} and the VMDI showed greater synchrony during that period (Fig. 5c), supporting this possibility.

Consistent with previous findings that the NPO/NPGO mode became more dominant in the North Pacific in recent decades (Di Lorenzo et al., 2010; Yeh et al., 2011) and that VM variability is projected to become more pronounced under future warming (Ji et al., 2024), the 30 year running correlation between coral-based NPGO–VM variability and CP-SST_{ERSST5} (Fig. 7a) reveals a strengthened and sustained relationship that began in the 1990s. This result suggests that the contribution of NPGO–VM to climate variability in the North Pacific or NWP has been robust in recent decades. A similar relationship was observed in the 30 year running correlations between coral-based NPGO–VM variability and other Pacific coral records that capture the NPGO-related signals (Palmyra-SST_{coral} and Clarion-$\delta^{18}O_{coral}$; Figs. 7b and 7c). These findings underscore the growing importance of NPGO–VM in climate–ocean interactions (Ji et al., 2024) and marine ecosystem dynamics (Kilduff et al., 2015) across the North Pacific and beyond. Additionally, the strength of correlations during the period from the 1920s to the 1950s was comparable to that observed in recent decades for all three 30 year running correlations (Fig. 7). This historical period of strong coupling coincided with a high occurrence ratio of CP-centred versus EP-centred ENSO events, as shown in instrumental records (Freund et al., 2019). As in recent decades, NPGO–VM variability and climate variability in the CP were also likely dominant in the North Pacific and the tropical Pacific, respectively, during the period from the 1920s to the 1950s.

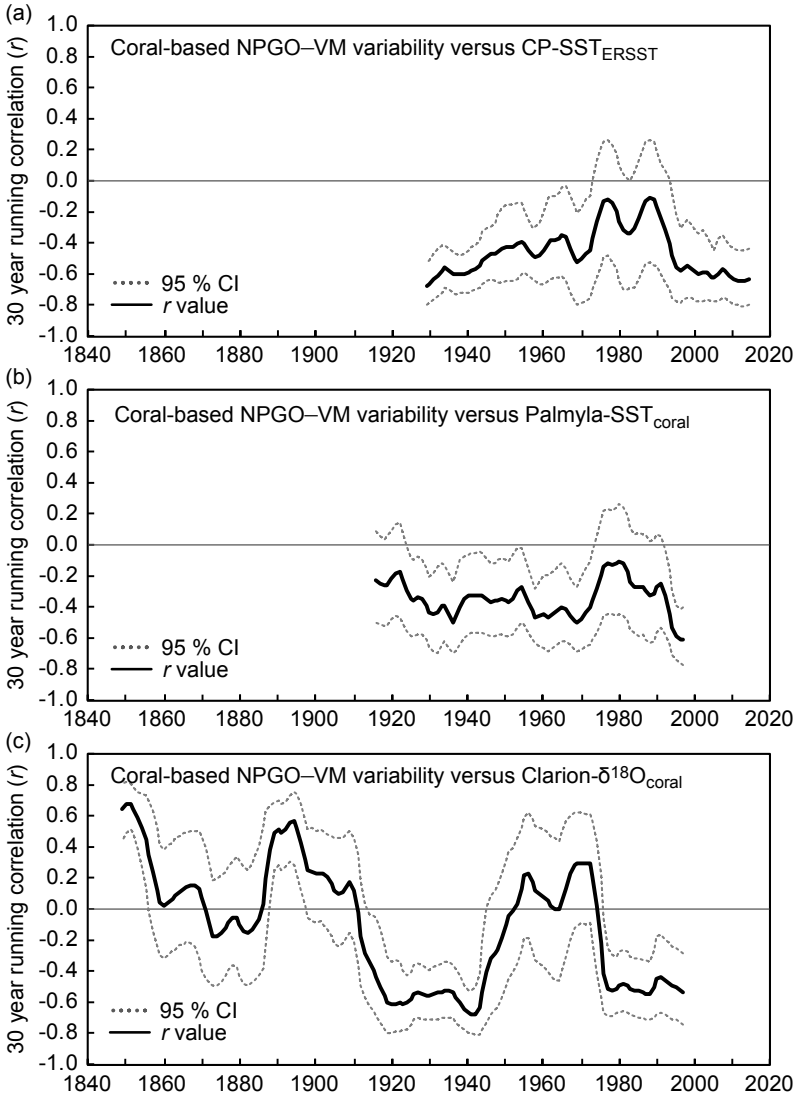

Figure 7. 30 year running correlation between coral-based NPGO–VM variability and the datasets from the CP/NEP region.

30 year running correlation between coral-based NPGO–VM variability and (a) CP-SST$_{ERSS5}$ (Huang et al., 2017), (b) Palmyra-SST$_{coral}$ (Nurhati et al., 2011), and (c) Clarion-δ^{18}O$_{coral}$ (Sanchez et al., 2016). The solid line represents the 30 year running correlation coefficient (*r*), and the dashed lines indicate the 95 % confidence interval (CI). An 8 year low-pass filter was applied to all time series prior to calculating the correlation.

4.4 Advantages of proxy-based reconstruction of NPGO–VM variability

Several proxy-based NPGO reconstructions have been developed in previous studies, including tree-ring-based records (Dong et al., 2022; Sakashita et al., 2017) and coral-based records (Nurhati et al., 2011; Rafter et al., 2017; Sanchez et al., 2016). The

previous coral-based reconstructions are derived from archives located primarily in the central tropical Pacific and eastern Pacific. In contrast, our study presents the first long-term reconstruction of the NPGO–VM variability based on the NWP coral archive.

The tree-ring-based reconstruction has the advantage of a long coverage period. Dong et al. (2022) reconstructed NPGO variability using tree-ring chronologies that extend back to 1596 CE. They identified negative-NPGO phases from the 1790s to the 1810s, which is consistent with the Dalton minimum (1790–1830 CE; Wagner and Zorita, 2005). However, our coral-based NPGO–VM variability did not indicate a distinct, consecutive negative-NPGO phase during that period (Fig. 6a). This discrepancy may be explained by differences in the characteristics of both proxies. As a tree-ring chronology is based on tree physiology, not on thermodynamic mechanisms, the records exhibit a large uncertainty (Björklund et al., 2023) and are influenced by other controlling factors (e.g., solar, thermal, and moisture factors; Evans et al., 2006; Mann et al., 2012). A long-term tree-ring-based reconstruction of temperature anomaly modes would be strengthened by combining with other temperature archives (e.g., corals or foraminifera). Coral skeletal growth and the skeletal geochemical record are also sometimes inhibited by thermal stress under extreme temperature conditions, observed as growth disturbances (e.g., stress bands, as reported by DeCarlo and Cohen, 2017) or anomalous seasonality (e.g., breakdown in seasonality, as reported by D'Olivo and McCulloch, 2017). In our study, our specimens did not show such anomalous signatures (Figs. 2 and A3); therefore, the potential influence of growth cessation on the skeletal geochemical proxy is considered negligible.

Sanchez et al. (2016) reported decadal NPGO variability based on coral $\delta^{18}O$ records (Clarion-$\delta^{18}O_{coral}$) derived from Clarion Island in the NEP. However, our coral-based NPGO–VM variability did not correlate with Clarion-$\delta^{18}O_{coral}$ (r = 0.22, N_{eff} = 26.07, *n.s.*, 8 year low-pass filtered; Figs. 6a and 6c). Even when using 8–30 year bandpass filtered datasets, Summer Kikai-SST_{coral} did not correlate significantly with Clarion-$\delta^{18}O_{coral}$ (Figs. A12b and A12d; Table 2c). Cross-wavelet coherence analysis further indicated that our coral-based NPGO–VM variability and the Clarion-$\delta^{18}O_{coral}$ were coherent at inter-decadal to decadal frequencies between 1820 and 1997 CE (Fig. 6e); however, the 30 year running correlation between coral-based NPGO–VM variability and Clarion-$\delta^{18}O_{coral}$ showed significant correlations only during limited periods, specifically the 1910s–1940s and the 1980s–1990s (Fig. 7c). These weak or intermittent correlations may result from fundamental differences in the primary controlling factors of coral Sr/Ca and $\delta^{18}O$. Coral Sr/Ca reflects only temperature variation (e.g., Corrège, 2006; Shen et al., 1996), whereas coral $\delta^{18}O$ is influenced by both temperature (negatively correlated, e.g., Abram et al., 2016; Watanabe et al., 2011) and $\delta^{18}O$ in seawater (positively correlated, e.g., Garas et al., 2023; Shen et al., 2005; Thompson et al., 2022). It is well established that the NPGO is also associated with changes in ocean salinity (Chhak et al., 2009; Di Lorenzo et al., 2009). Clarion Island is located at the termination of the California Current System, which is characterised by cooler (warmer) and higher (lower) salinity water during positive- (negative-) NPGO phases (Di Lorenzo et al., 2008; Sanchez et al., 2016). Therefore, the complexity arising from multiple controlling factors of coral $\delta^{18}O$ may reduce the signal-to-noise ratio in capturing NPGO-related temperature and salinity signals.

Compared to tree-ring- or coral $\delta^{18}O$-based NPGO reconstructions, coral Sr/Ca, an oceanic temperature proxy, is likely to provide greater reliability. This advantage arises because coral Sr/Ca directly reflects SST variability and therefore serves as

an effective archive of large-scale ocean circulation and temperature anomaly modes, such as the NPGO and VM. Nurhati et al. (2011) documented a coral Sr/Ca-based temperature record (Palmyra-SST_{coral}) from Palmyra Island in the CP that exhibits a strong relationship with the NPGO at the decadal timescale, reflecting dynamical linkages between temperature variability in the CP and extratropical decadal climate variability. We found a significant correlation between Summer Kikai-SST_{summer} and Palmyra-SST_{coral} for the period from 1887 to 1997 CE with an 8–30 year bandpass filter (Figs. A12a and A12c; Table 2c), whereas no significant correlation was observed between our coral-based NPGO–VM variability and Palmyra-SST_{coral} with an 8 year low-pass filter (r = –0.31, N_{eff} = 18.02, *n.s.*; Figs. 6a and 6b). Cross-wavelet coherence analysis further indicated that the coral-based NPGO–VM variability and Palmyra-SST_{coral} records were coherent at very limited periods and frequencies between 1887 and 1997 CE (Fig. 6d). This weak correspondence is most likely attributable to differences in the dominant variability in the two datasets, arising from the use of different temporal pass filters (i.e., an 8–30 year bandpass filter versus an 8 year low-pass filter). Nevertheless, when the coral Sr/Ca–based temperature records from both Palmyra Island in the CP and Kikai Island in the NWP are considered together, they provide complementary evidence for the long-term propagation of an extratropical temperature component via the "ocean–atmosphere bridge (Sect. 4.1.1)." The consistency of these relationships across spatially separated regions supports the existence of a CP–NWP teleconnection, consistent with NPGO-mode-centred Pacific decadal dynamics and associated ocean–atmosphere coupling (Di Lorenzo et al., 2013). Overall, the key strength of the coral Sr/Ca-based reconstruction lies in its direct sensitivity to oceanic temperature variability, making it particularly well suited for identifying large-scale ocean–atmosphere modes such as the NPGO and VM.

5 Conclusion

We presented a new long-term NPGO–VM-related temperature variability based on reef-building coral skeletons collected at Kikai Island in the NWP, extending back to the 19th century. Our Summer Kikai-SST_{coral} showed significant correlations with temperature variability in the CP, the NPGO Index, and the VMDI. These findings suggest an extra-tropical propagation of NPGO–VM-related temperature variation from the CP to the NWP via the ocean-atmosphere bridge. Over the past 200 years, the NPGO–VM has had a significant prominence in the Pacific, with the exception of the period from the 1970s to the 1980s. Furthermore, the relationship between NPGO–VM and temperature anomalies in the CP has become robust since the 2000s, aligning with previous findings (e.g., Yeh et al., 2011). Additionally, pronounced negative-NPGO/positive-VM phases (cool-temperature in the NWP) were identified during the 1860s–1900s. This phase may have contributed to the delayed onset of the warming trend in the NWP.

The NPGO–VM has the potential to influence global-scale climate variability through its strong linkage with temperature anomalies in the CP (Di Lorenzo, 2013). Its impact extends beyond temperature variability in the North Pacific and NWP, affecting hydrological conditions in regions such as East Asia (e.g., Ye et al., 2016). Given this strong linkage between the CP and NPGO–VM, as well as the projected increase in the frequency of CP-centred ENSO events, the prominence of NPGO–VM in the North Pacific, NWP, and East Asia is expected to be more significant under future warming scenarios. Despite the

recognised importance of the NPGO–VM, our coral record represents the first reconstruction of past NPGO–VM-related temperature variability. To improve our understanding of this ocean-atmosphere mode, more reconstructions are needed across broader spatiotemporal scales that can cover a wide region in the Pacific and over centennial timescales, using temperature proxies. As yet, century-long temperature records at high temporal resolution (monthly to seasonal) that complement or extend beyond the instrumental period (pre-1900s) remain scarce in the NWP. As shown in this study, coral skeletons provide an ideal archive for directly capturing ocean circulation and temperature anomaly modes, such as NPGO–VM. However, because the NWP lies near the northern limit of reef-building coral distribution and coral geochemical records may be affected by seasonal growth-related biases, particularly in winter, future efforts would benefit from multi-proxy approaches. Coral records combined with other high-resolution marine archives, such as bivalves (e.g., Tanabe et al., 2017), coralline algae (e.g., Hetzinger et al., 2009), and sclerosponges (e.g., Asami et al., 2017), will help overcome spatial limitations, reduce proxy-specific biases and enhance reconstruction robustness.

Appendices

Table A1. Abbreviation term list for datasets.

All datasets are shown in figures and tables in the main text or Appendices.

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Abbreviation term	Reference	Notes
(a) Sea surface temperature (SST) datasets		
Kikai-SST_{ERSST5}	Huang et al. (2017)	Instrumental SST record for the grid cell that includes the coral sampling site, Kikai Island (ERSST5, 27–29° N, 129–131° E). See also Sect. 2.4.
CP-SST_{ERSST5}	Huang et al. (2017)	Instrumental SST record for the CP (ERSST5, 5° S–5° N, 160° E–150° W). See also Sect. 2.4.
Summer Kikai-SST_{coral}	This study	Coral Sr/Ca-based SST record from Kikai Island. Calculated by converting Kikai-coral Sr/Ca_{summer} into temperature. See also Sect. 2.5.
Winter Kikai-SST_{coral}	This study	Coral Sr/Ca-based SST record from Kikai Island. Calculated by converting Kikai-coral Sr/Ca_{winter} into temperature. See also Sect. 2.5.
(b) Coral Sr/Ca datasets		
Kikai-coral Sr/Ca	This study	Coral skeletal Sr/Ca record (1798–2015 CE) from Kikai Island in the NWP.
Kikai-coral Sr/Ca_{summer}	This study	Extracted dataset of boreal summer values (3 month averaged) from Kikai-coral Sr/Ca.
Kikai-coral Sr/Ca_{winter}	This study	Extracted dataset of boreal winter values (3 month averaged) from Kikai-coral Sr/Ca.
Kikai-coral $Sr/Ca_{annual\ mean}$	This study	Annual mean dataset of Kikai-coral Sr/Ca, calculated by averaging values from one winter peak to the subsequent winter peak.
(c) Others		
Palmyra-SST_{coral}	Nurhati et al. (2011)	Coral Sr/Ca-based temperature reconstruction from Palmyra Island in the CP.
Clarion-$\delta^{18}O_{coral}$	Sanchez et al. (2016)	Coral $\delta^{18}O$-based NPGO variability reconstruction from Clarion Island in the NEP.
Coral-based NPGO–VM variability	This study	Calculated by 8 year low-pass filtered datasets of Kikai-coral Sr/Ca_{summer}. See also Eq.1 and Sect. 2.7 in the main text.

Table A2. Determined coral uranium and thorium isotopic compositions and ^{230}Th ages.

The dating was carried out using MC-ICP-MS (Thermo Electron Neptune) installed at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), National Taiwan University (see also Sect. 2.3). Over the past few decades, HISPEC has carefully addressed potential biases and uncertainties of the initial ^{230}Th, and has also resolved instrumental ghost signals (Cheng et al., 2013; Shen et al., 2002; Shen et al., 2008; Shen et al., 2012). The verification of the fidelity of dating young coral by MC-ICP-MS techniques was rigorously conducted and reported by Shen et al. (2008) and Shen et al. (2012).

Sample	Weight	^{238}U	^{232}Th	δ^{234}U	[^{230}Th/^{238}U]	[^{230}Th/^{232}Th]	Age (CE)	$\delta^{234}U_{initial}$
ID	g	10^{-9}g/g [a]	10^{-12}g/g	measured[a]	activity[c]	atomic (x 10^{-6})	corrected[c,d]	corrected[b]
KISM-1	0.2064	3044.1 ± 4.2	273.9 ± 2.3	146.1 ± 1.6	0.001408 ± 0.000011	258.0 ± 3.0	1884.3 ± 1.5	146.2 ± 1.6
KISM-2	0.1740	2600.4 ± 2.7	397.5 ± 2.7	147.3 ± 1.6	0.001451 ± 0.000018	156.5 ± 2.2	1883.1 ± 2.5	147.3 ± 1.6
KISM-3	0.4134	2744.6 ± 2.5	320.0 ± 1.2	145.1 ± 1.5	0.002337 ± 0.000023	330.4 ± 3.5	1797.5 ± 2.6	145.2 ± 1.5

Note. Chemistry was performed in March 2016 and July 2017 (Shen et al., 2003), and instrumental analysis on MC-ICP-MS (Shen et al., 2012). Analytical errors are 2σ of the mean.

[a] $[^{238}U] = [^{235}U] \times 137.77$ (± 0.11 ‰) (Hiess et al., 2012); $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$.

[b] $\delta^{234}U_{initial}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda 234 * T}$, and T is corrected age.

[c] $[^{230}Th/^{238}U]_{activity} = 1 - e^{-\lambda 230 T} + (\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda 230 - \lambda 234) T})$, where T is the age.

Decay constants are 9.1705 x 10^{-6} yr^{-1} for ^{230}Th, 2.8221 x 10^{-6} yr^{-1} for ^{234}U (Cheng et al., 2013), and 1.55125 x 10^{-10} yr^{-1} for ^{238}U (Jaffey et al., 1971).

[d] Age corrections were calculated using an estimated atomic ^{230}Th/^{232}Th ratio of 4 (± 2) x 10^{-6} (Shen et al., 2008).

Table A3. The difference in coral Sr/Ca for overlapping periods.

Mean values of overlapped Sr/Ca record between (a) Core-1 and Core-2, (b) Core-2 and Core-3. "Summer (Winter) peaks mean" means the average value of the annual lowest (highest) Sr/Ca in the overlapped periods. "Difference" values were shown in absolute values calculated by subtracting cores. The asterisk (*) indicates a significant difference (*p*-value < 0.05, *t*-test). The time series is shown in Fig. A6.

(a) Overlap between Core-1 and Core-2 (1926–1931 CE)			
	Mean (mmol mol^{-1})	Summer peaks mean (mmol mol^{-1})	Winter peaks mean (mmol mol^{-1})
Core-1	9.16	8.97	9.43
Core-2	9.21	8.98	9.52
Difference	0.05	<0.01	0.08*

(b) Overlap between Core-2 and Core-3 (1881–1884 CE)			
	Mean (mmol mol^{-1})	Summer peaks mean (mmol mol^{-1})	Winter peaks mean (mmol mol^{-1})
Core-2	9.36	9.06	9.67
Core-3	9.27	9.05	9.55
Difference	0.09	0.01	0.12

Table A4. Comparison of modern coral Sr/Ca records from Kikai Island.

Both coral Sr/Ca records were from *Porites* corals. Sample collection sites are shown in Fig. A2. The coral core of this study was collected on the northeastern side (Shiomichi Bay) of Kikai Island. The coral core of Morimoto et al. (2007) was collected on the southwestern side (offshore of Arakizaki Point) of Kikai Island. The seasonal range was calculated by the difference between (a) and (b).

	(a) Mean value of the annual lowest Sr/Ca (mmol mol^{-1})	(b) Mean value of the annual highest Sr/Ca (mmol mol^{-1})	(c) Seasonal range: (b) – (a) (mmol mol^{-1})
This study (Core-1)	8.947	9.518	0.571
Morimoto et al. (2007)	8.852	9.382	0.530

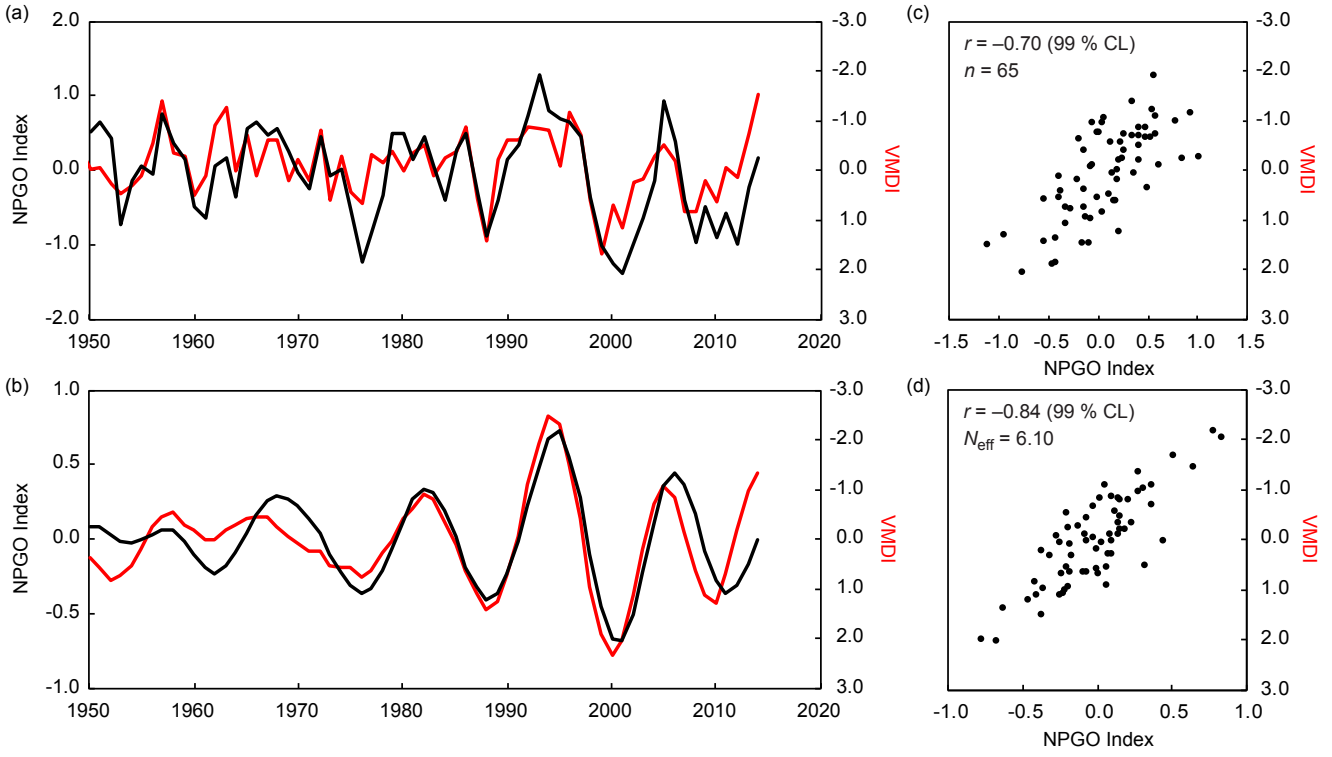

Figure A1. Comparison of the NPGO Index and VMDI time series.

(a) The time series of annual mean NPGO Index (Di Lorenzo et al., 2008, in black) and annual mean VMDI (Wen et al., 2004, calculated using ERSST5 dataset, in red). (b) Same as (a), but the 8–30 year bandpass filtered time series. The filtering method is described in Sect. 2.6. (c)(d) Scatter plots corresponding to (a) and (b). See also Sect. 2.6 for statistical analysis.

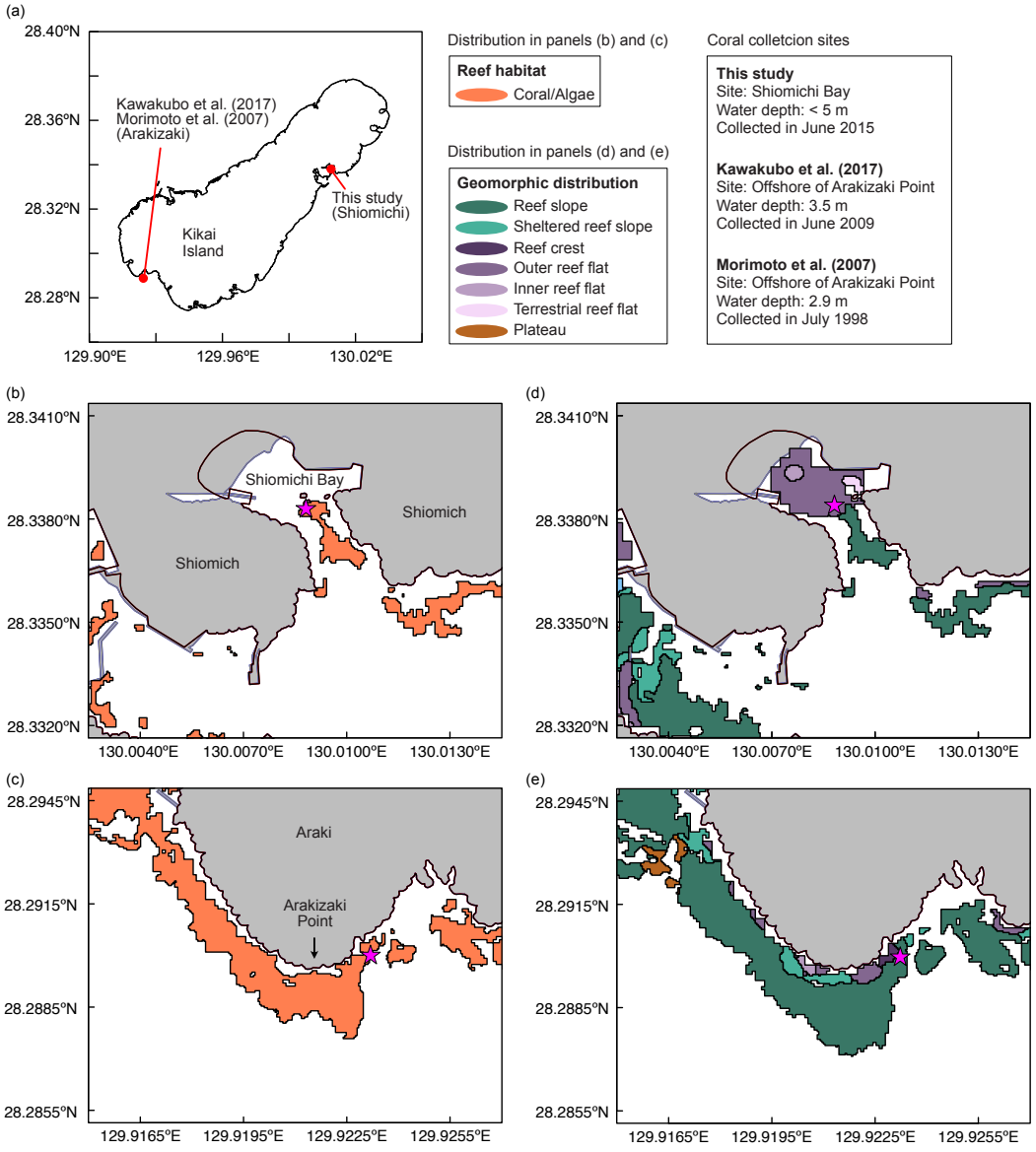

Figure A2. Maps of coral core collection sites for this study and previous studies.

(a) Map of Kikai Island, Kagoshima, Japan. Red circles mark sites of coral core collection for this study (Shiomichi Bay) and for previous studies (Kawakubo et al., 2017; Morimoto et al., 2007; offshore of Arakizaki Point). The site for the previous studies was referred to the location introduced in Morimoto et al. (2007) and Kubota et al. (2017). (b) Reef habitat distribution (coral/algae) for Shiomichi Bay. The reef habitat dataset was derived from The Allen Coral Atlas (Lynos et al., 2024). Star marks the coral core collection site. The distribution legends are shown above. (c) Same as (b), but for offshore of Arakizaki Point. (d) Geomorphic distribution for Shiomichi Bay. The geomorphic zonation dataset was derived from The Allen Coral Atlas (Lynos et al., 2024). (e) Same as (d), but for offshore of Arakizaki Point. For all panels, the coastline data were derived from the National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan (https://nlftp.mlit.go.jp/index.html). The grey-coloured coastal line and grey-shaded land were based on the latest data (2023 CE). The black line depicts coastal line prior to 2000 CE. In the Shiomichi area, land reclamation along the coast, facing to Shiomichi Bay was conducted in 2003 CE.

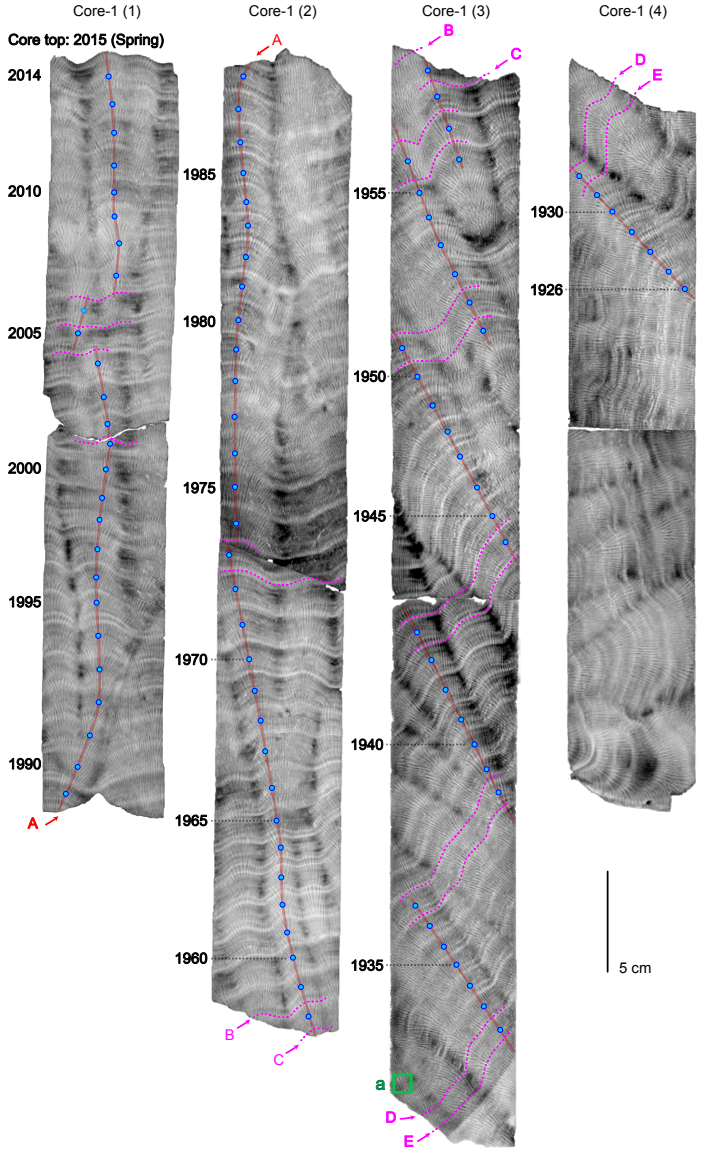

Figure A3. X-radiographs of the *Porites* coral specimens.

The X-radiographs (negative) show subsampling paths indicated by red lines. The red arrows and accompanying capital letters denote the continuation of a subsampling path onto the next slab. The magenta dashed lines and accompanying capital letters mark high-density bands that help connect subsampling paths. In Core-1 and Core-3, the blue circles are marked between high-density bands, corresponding to the annual cycles identified in the skeletal Sr/Ca record. The subsampled locations for U–Th dating are marked with red circles and labelled with numbers (Sample IDs: 1 = "KISM-1", 2 = "KISM-2", and 3 = "KISM-3"); the dating results are listed in Table A2. The positions used for diagenesis screening are shown as green squares and lowercase letters. The years estimated by seasonal cycles in skeletal Sr/Ca are shown left of each slab. This figure continues on the following two pages.

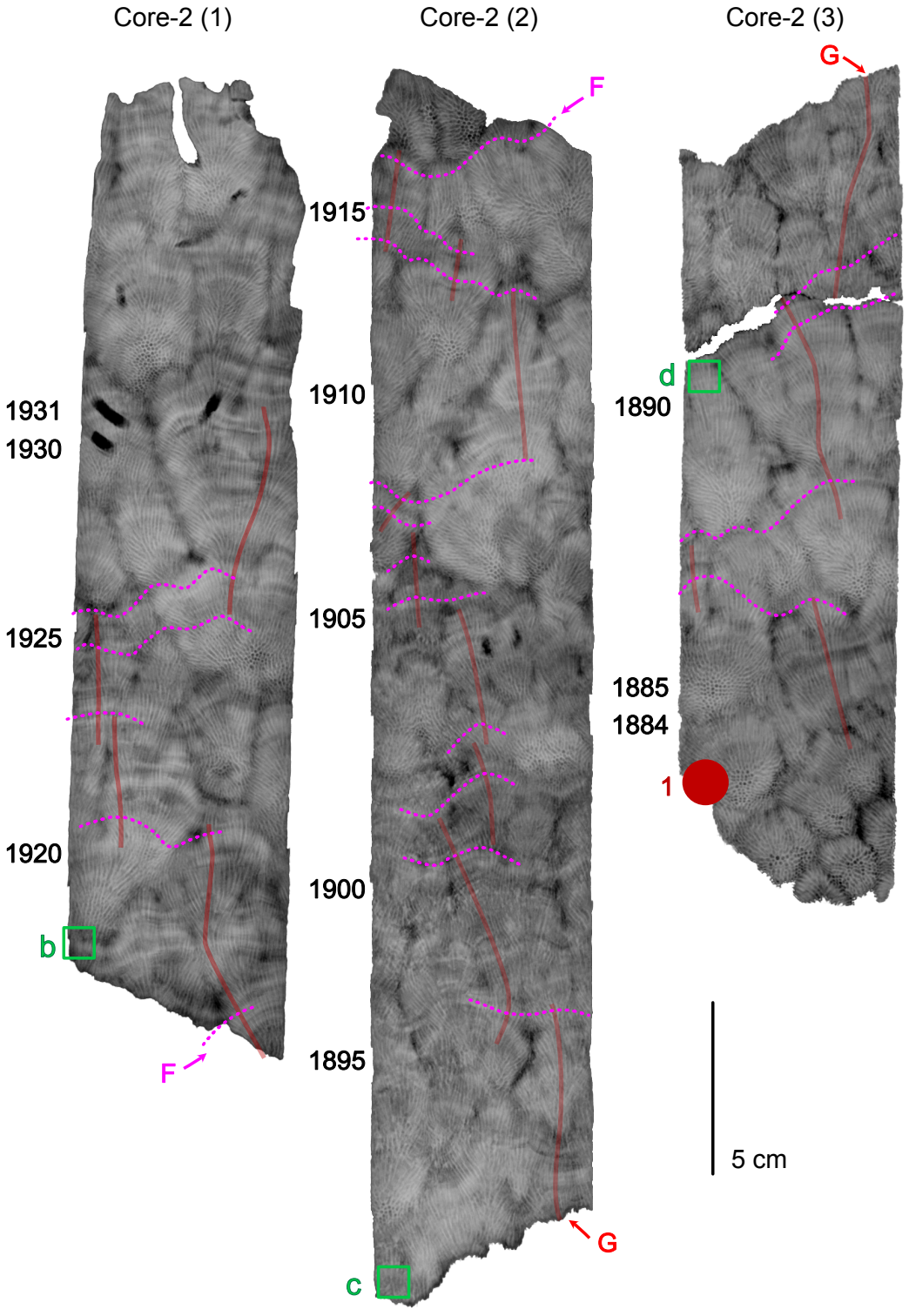

Figure A3. X-radiographs of the *Porites* coral specimens. (continued)

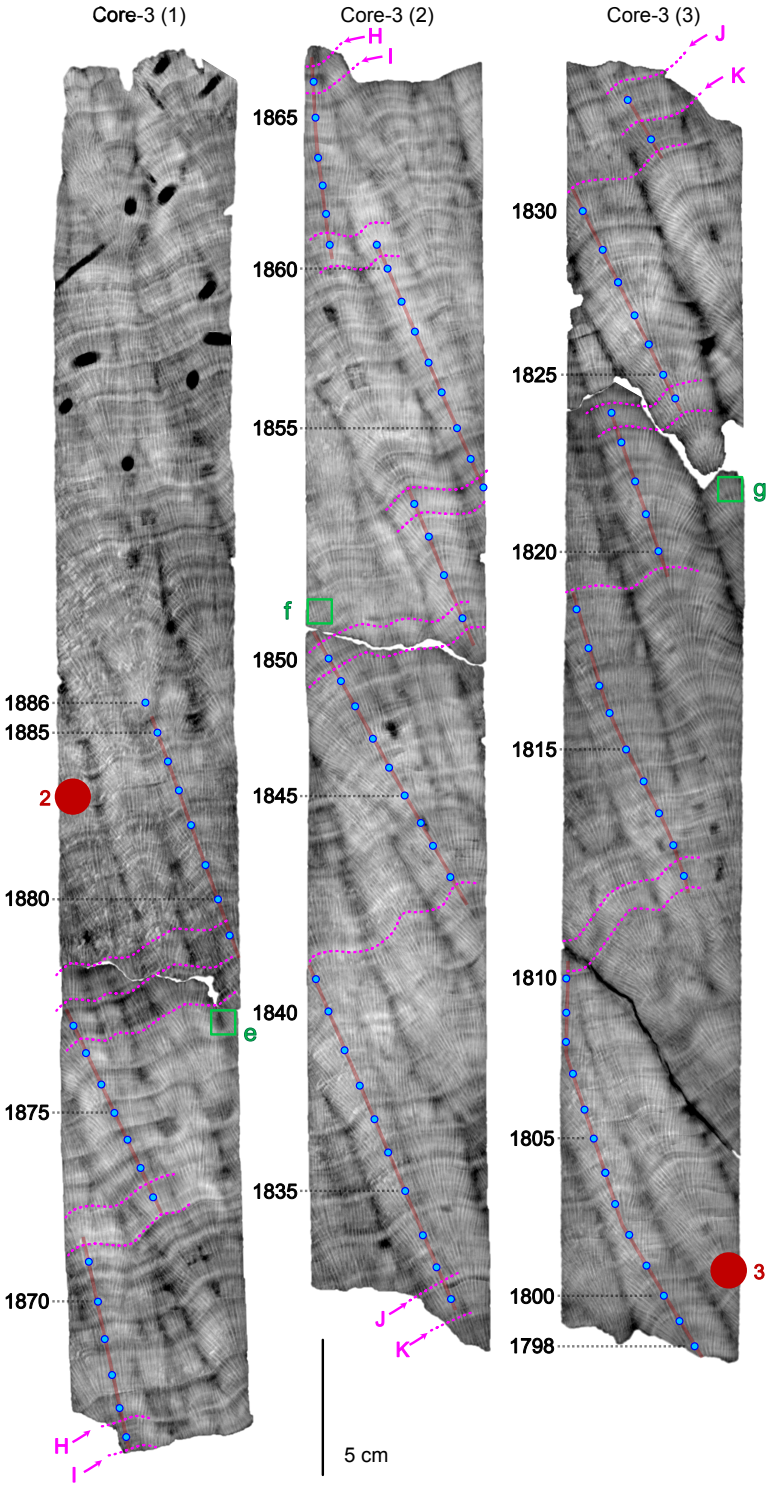

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Figure A3. X-radiographs of the *Porites* coral specimens. (continued)

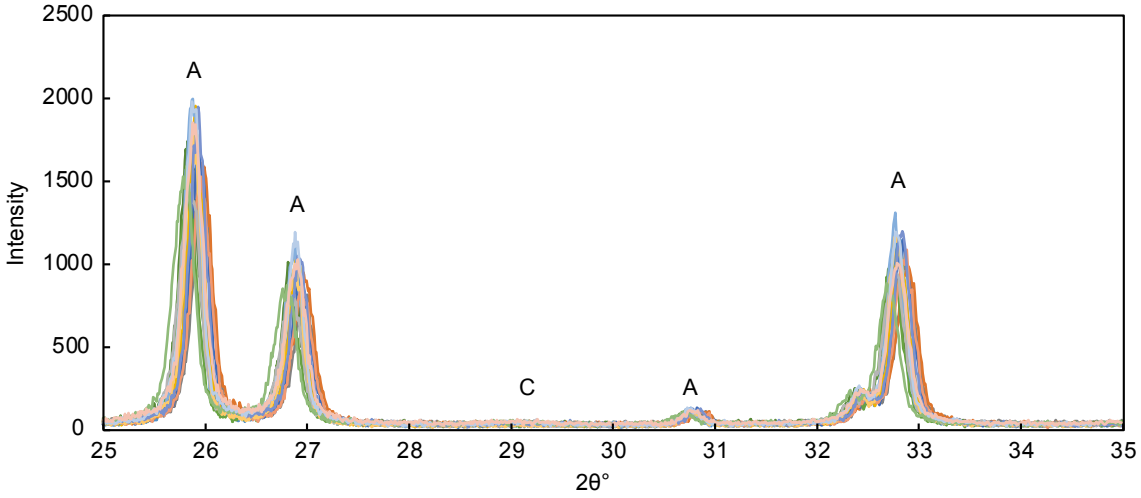

Figure A4. Diagenesis screening by X-ray diffraction analysis.

Powder samples for X-ray diffraction analysis were collected along all analytical paths shown in Fig. A3. Notes "A" and "C" indicate the diffraction angles (2θ) corresponding to aragonite and calcite, respectively. The resulting peaks labelled "A" confirm that the crystalline structure of the samples is aragonite. No calcite peaks ("C") were observed in any of the samples. The calcite content for each analytical line was less than 1 %. Based on these results, we concluded that pristine aragonite is well preserved throughout all analytical paths.

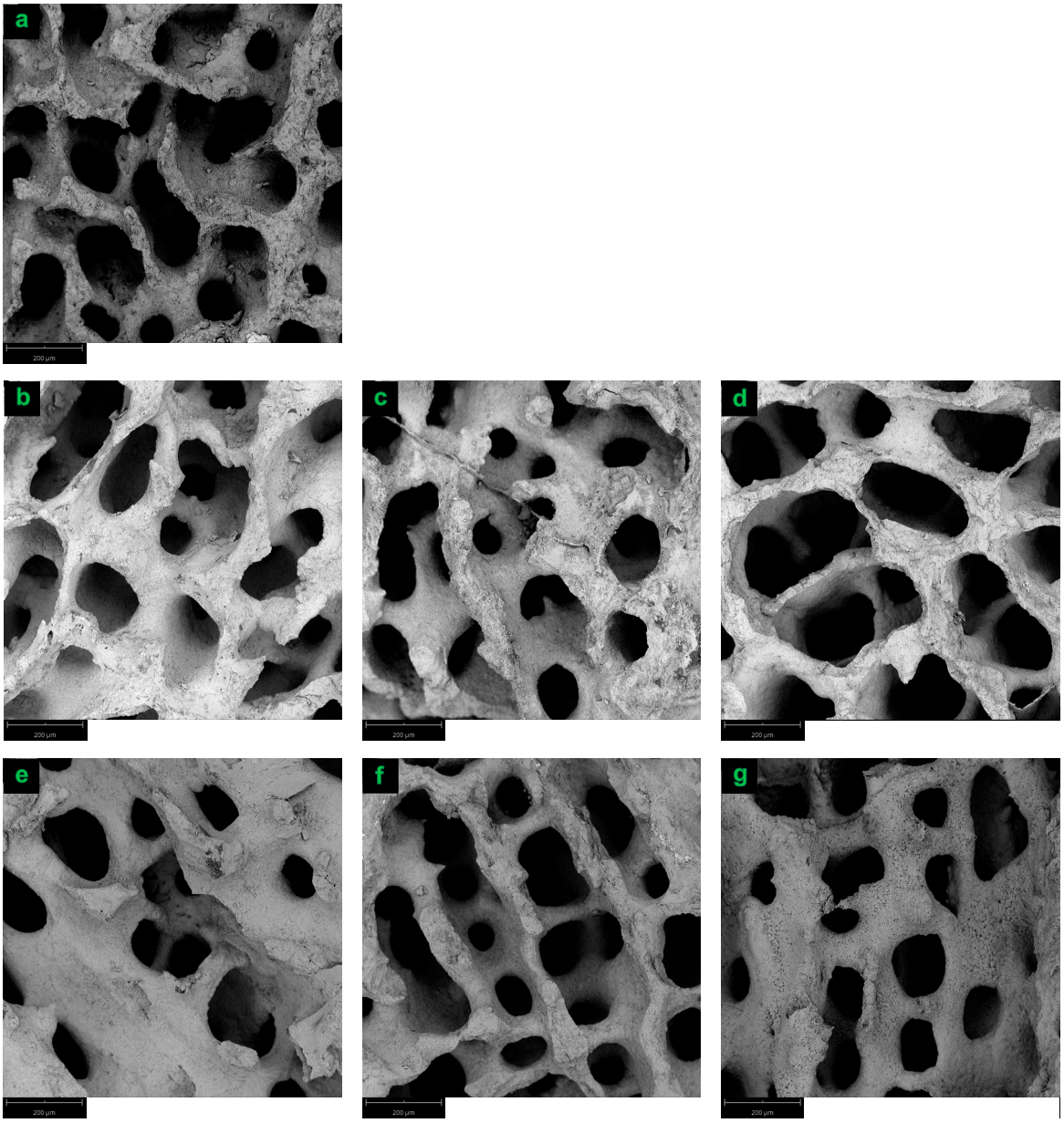

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Figure A5. Diagenesis screening by scanning electron microscopy.

The locations where each image was taken are shown in Fig. A3. (a) Core-1. (b)(c)(d) Core-2. (e)(f)(g) Core-3. These images show little to no evidence of diagenetic alteration, such as the presence of calcite, secondary aragonite, and dissolution. The results indicate that pristine aragonite is well preserved in all specimens.

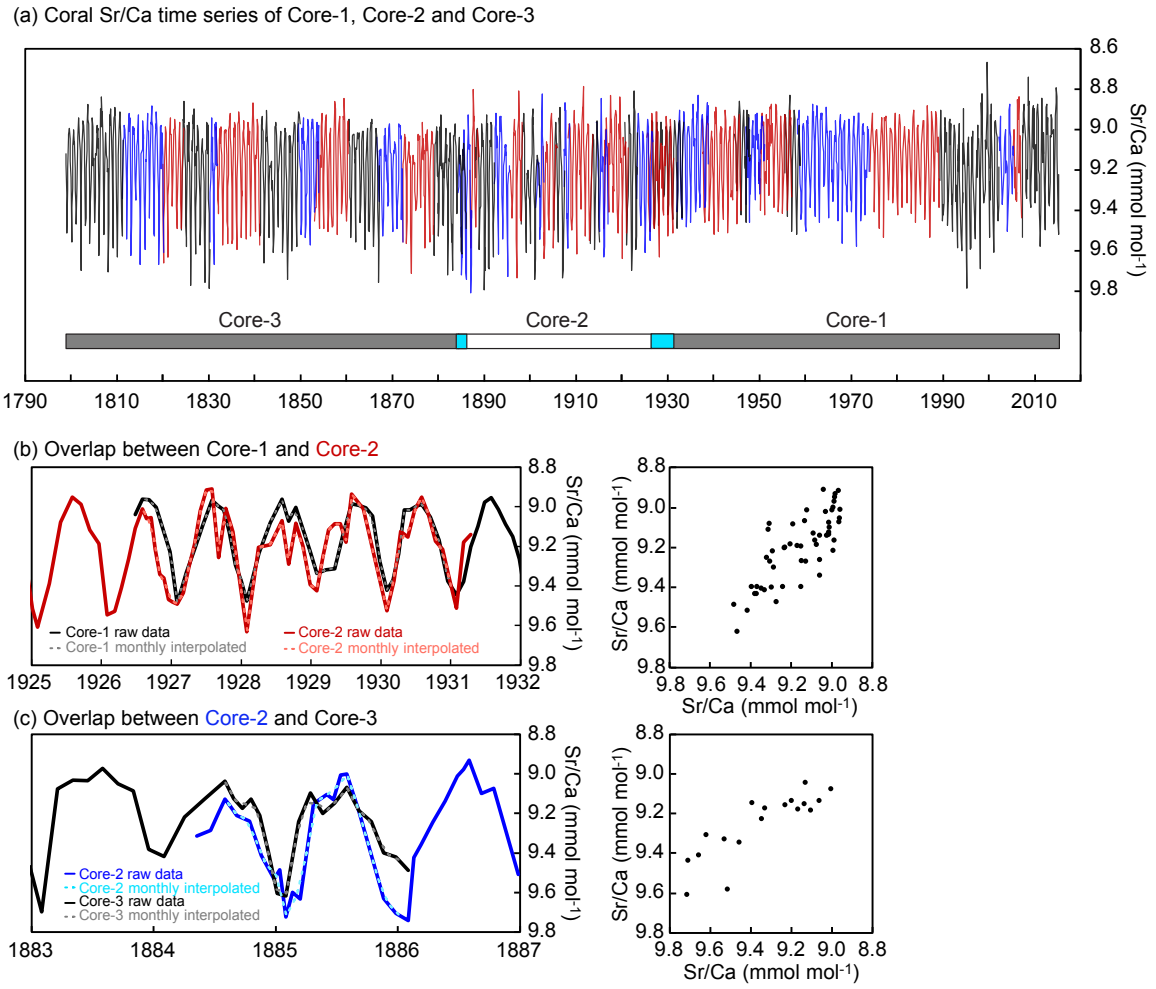
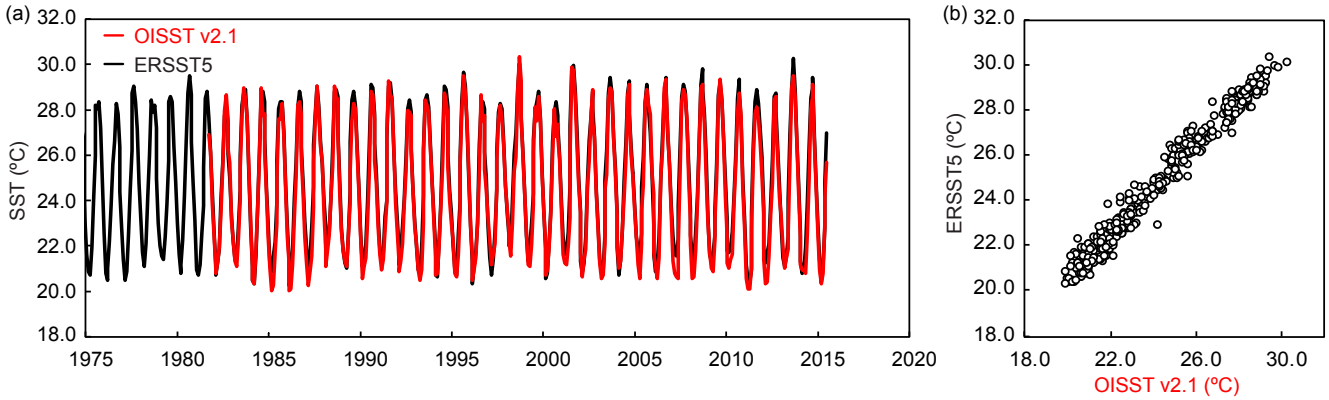


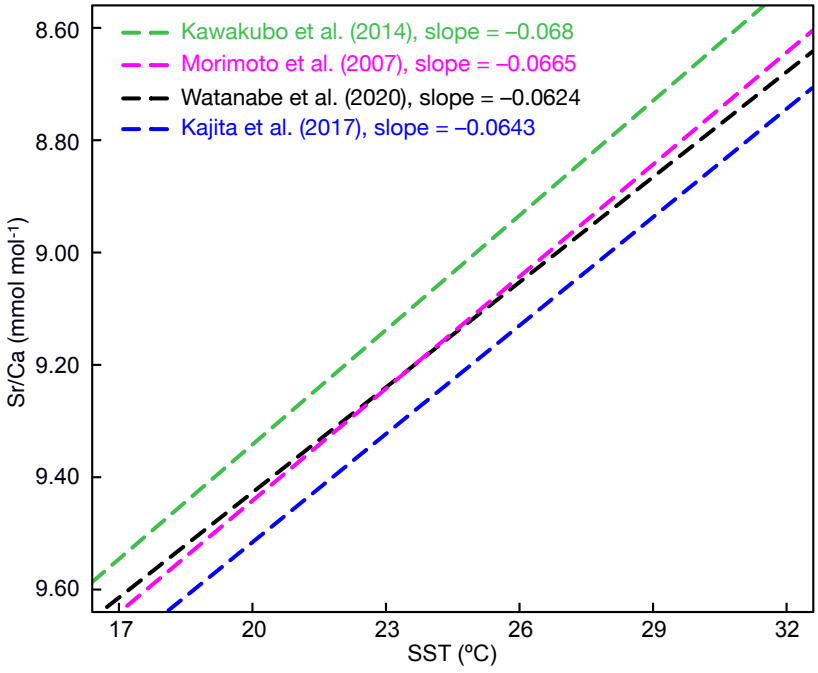
Figure A6. Individual coral Sr/Ca time series from three cores and their overlapping periods.

(a) Coral Sr/Ca time series from Core-1, Core-2, and Core-3. Sampling transects are highlighted in different colours (in black, red, or blue). The overlapping segments of cores are shown in pale blue bars (bottom). The mean annual growth rate for each core was 11.1 ± 2.53 mm year^{-1}, 14.7 ± 3.35 mm year^{-1}, and 13.2 ± 1.94 mm year^{-1} for Core-1, Core-2, and Core-3, respectively. (b) Left: Overlapping period between Core-1 and Core-2. Monthly interpolated coral Sr/Ca datasets of the overlapping periods are shown in grey and pale red. Right: Scatter plot of the monthly interpolated dataset. (c) Same as (b), but for the overlapping period between Core-2 and Core-3. Monthly interpolated datasets of the overlapping periods are shown in grey and pale blue. The differences in mean, summer, and winter Sr/Ca values between Core-1, Core-2, and Core-3 are reported in Table A3.



735 **Figure A7. Comparison of instrumental temperature products (OISST v2.1 and ERSST5, covering Kikai Island).**

(a) Time series of OISST v2.1 (Huang et al., 2021, monthly resolved and converted from daily data, for the 0.25° × 0.25° grid centred 28.375° N, 130.25° E, in red) and ERSST5 (Huang et al., 2017, for the grid of 27–29° N, 129–131° E, in black). (b) Scatter plots for OISST v2.1 and ERSST5 for the period 1982–2014 CE.



740 **Figure A8. Previously published coral Sr/Ca-temperature slopes for Kikai Island.**

Slopes reported by Kawakubo et al. (2014) (by laser ablation ICP-MS analysis, in green), Morimoto et al. (2007) (by TIMS analysis with the isotope dilution method, in magenta), Watanabe et al. (2020) (by solution ICP-OES analysis, in black), and Kajita et al. (2017) (by solution ICP-OES analysis, in blue) are shown. These slopes were used to convert skeletal Sr/Ca values (mmol mol^{-1}) into temperature units (°C) in this study.

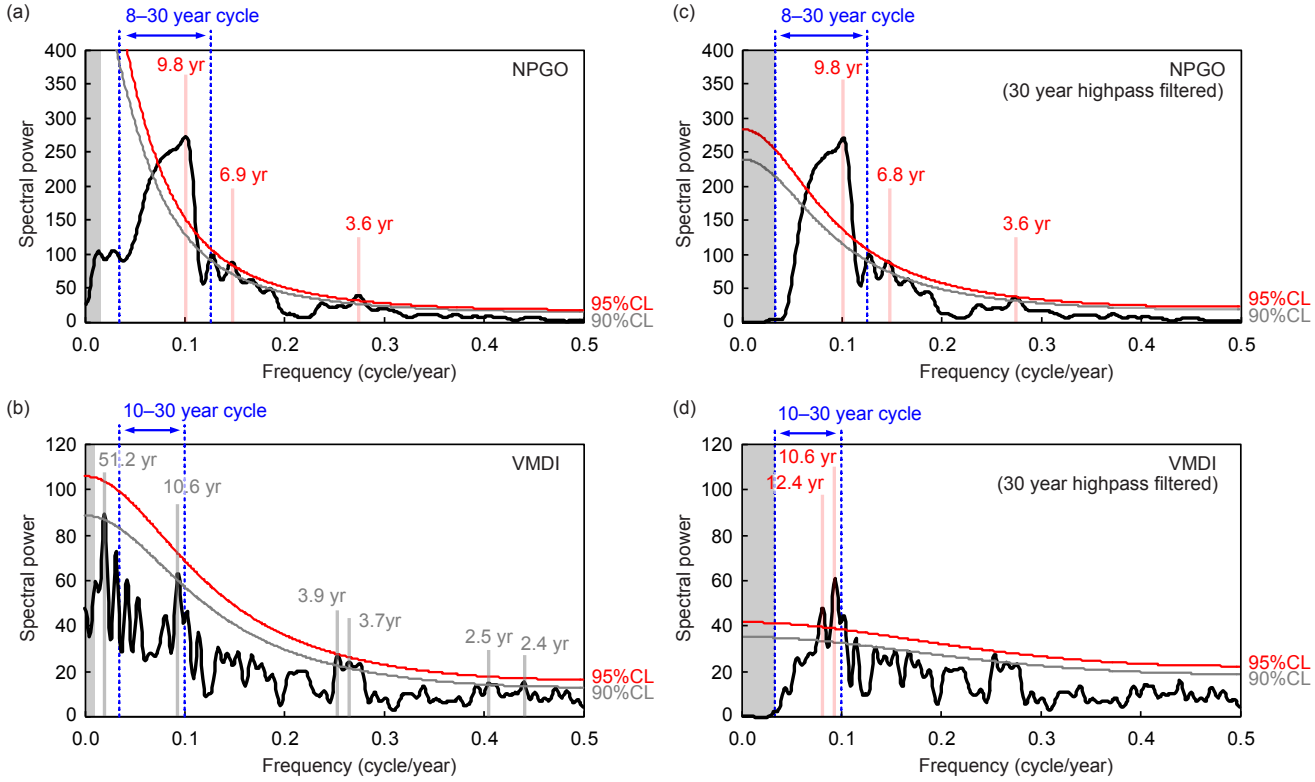


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Figure A9. Spectral power analysis for the NPGO Index and the VMDI

(a) Annual mean dataset of the NPGO Index (Di Lorenzo et al., 2008) for the period from 1950 to 2014 CE. (b) Annual mean dataset of the Victoria Mode Dipole Index (VMDI; Wen et al., 2024, calculated using ERSST5) for the period from 1900 to 2014 CE. (c)(d) Same as (a) and (b), but for the 30 year high-pass filtered dataset. The detected significant frequencies at the 95 % CL are denoted
750 **with years (yr, in red). Only in panel (b), the detected significant frequencies at the 90 % CL are denoted with years (yr, in grey). Indetectable frequencies are shaded in grey. The time frequency between the blue dashed lines with a note ("8–30 year cycle" or "10–30 year cycle") indicates the range of the pass filter that is employed in this study.**

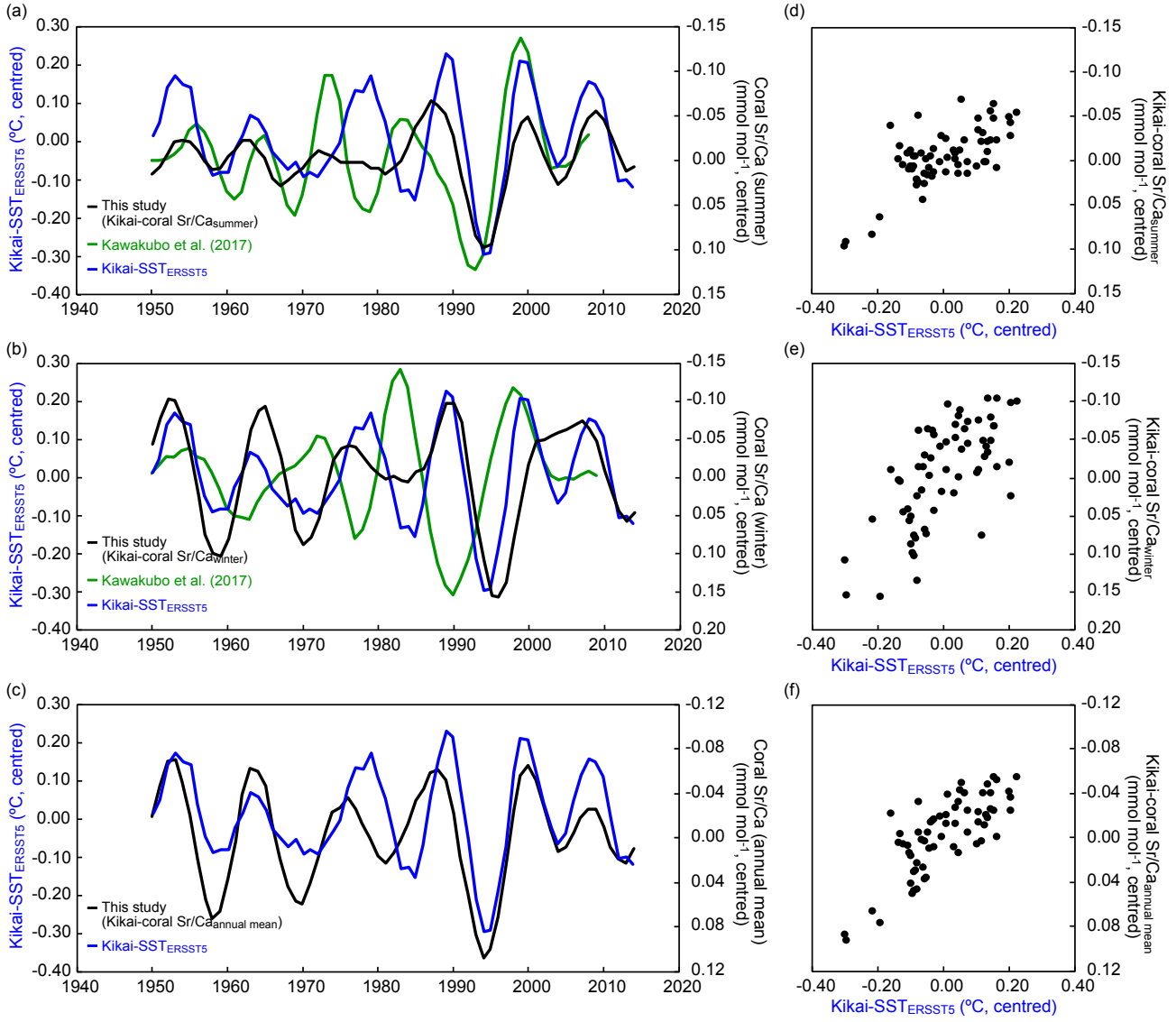

Figure A10. Comparison of coral Sr/Ca records with Kikai-SST$_{ERSST5}$.

The Kikai-SST$_{ERSST5}$ time series (in blue, annual mean; Huang et al., 2017) is compared with the following coral Sr/Ca records: (a) Kikai-coral Sr/Ca$_{summer}$ (in black, this study) and the previously summer published data (in green, Kawakubo et al., 2017); (b) Kikai-coral Sr/Ca$_{winter}$ (in black, this study) and the previously published winter data (in green, Kawakubo et al., 2017); (c) Kikai-coral Sr/Ca$_{annual mean}$ (in black, this study). An 8–30 year bandpass filter was applied to all time series. (d)(e)(f) Scatter plots of annual mean Kikai-SST$_{ERSST5}$ and our coral records (d: Kikai-coral Sr/Ca$_{summer}$; e: Kikai-coral Sr/Ca$_{winter}$; f: Kikai-coral Sr/Ca$_{annual mean}$).

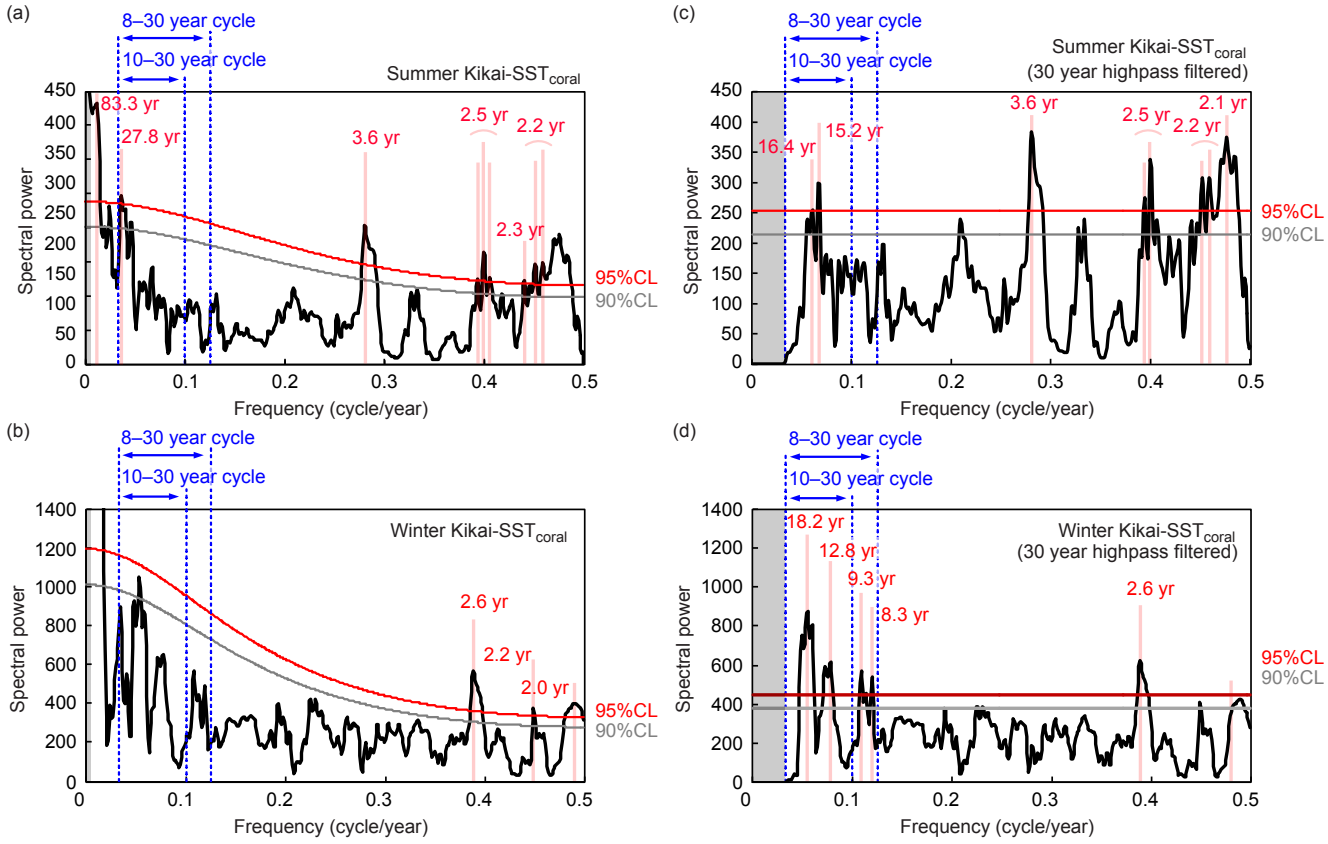

Figure A11. Spectral power analysis for Kikai-SST$_{coral}$ record

(a) Summer Kikai-SST$_{coral}$ and (b) Winter Kikai-SST$_{coral}$ datasets for the period from 1799 to 2014 CE. (c)(d) Same as (a) and (b), but for the 30 year high-pass filtered dataset. The detected significant frequencies at the 95 % CL are denoted with years (yr, in red). Indetectable frequencies are shaded in grey. The time frequency between the blue dashed lines with a note ("8–30 year cycle" or "10–30 year cycle") indicates the range of the pass filter that is employed in this study.

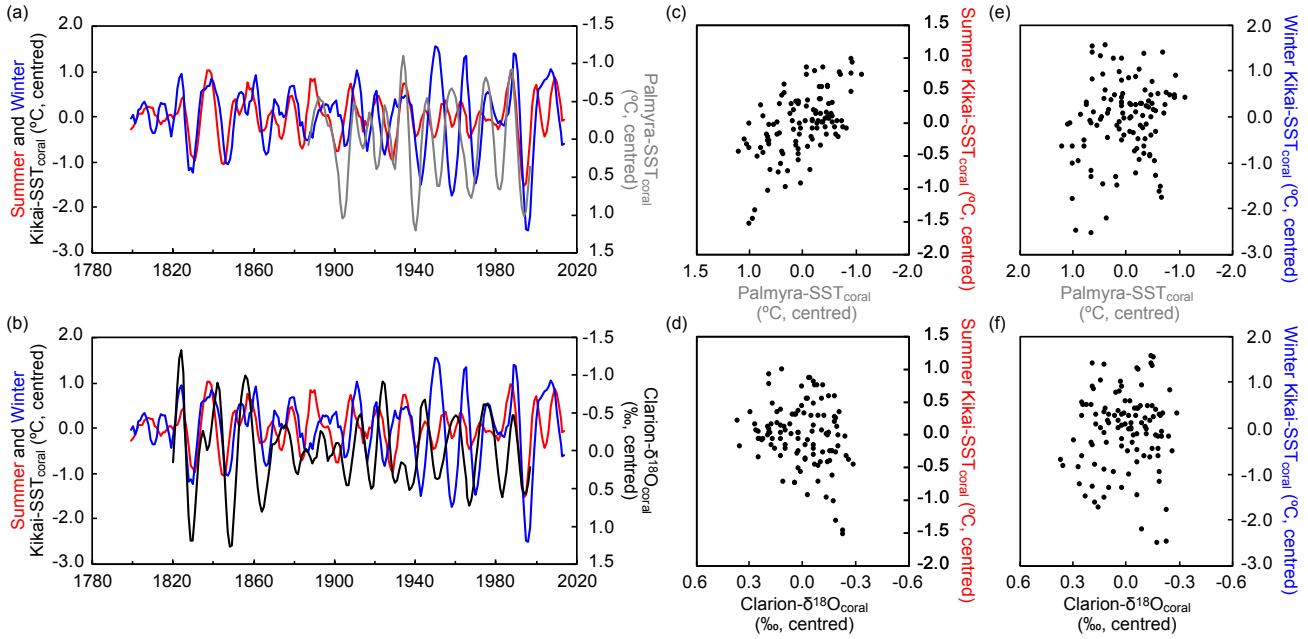

Figure A12. Comparison of the time series between our coral record from the NWP and the previously published coral record from the CP.

(a) Time series of Summer Kikai-SST$_{coral}$ (in red, this study), Winter Kikai-SST$_{coral}$ (in blue, this study), and Palmyra-SST$_{coral}$ (in grey, annual mean values, Nurhati et al., 2011). (b) Time series of Summer Kikai-SST$_{coral}$ (in red, this study), Winter Kikai-SST$_{coral}$ (in blue, this study), and Clarion-δ^{18}O$_{coral}$ (in black, annual mean values, Sanchez et al., 2016). An 8–30 year bandpass filter was applied to both time series. (c)(d)(e)(f) Scatter plot corresponding to (a) and (b).

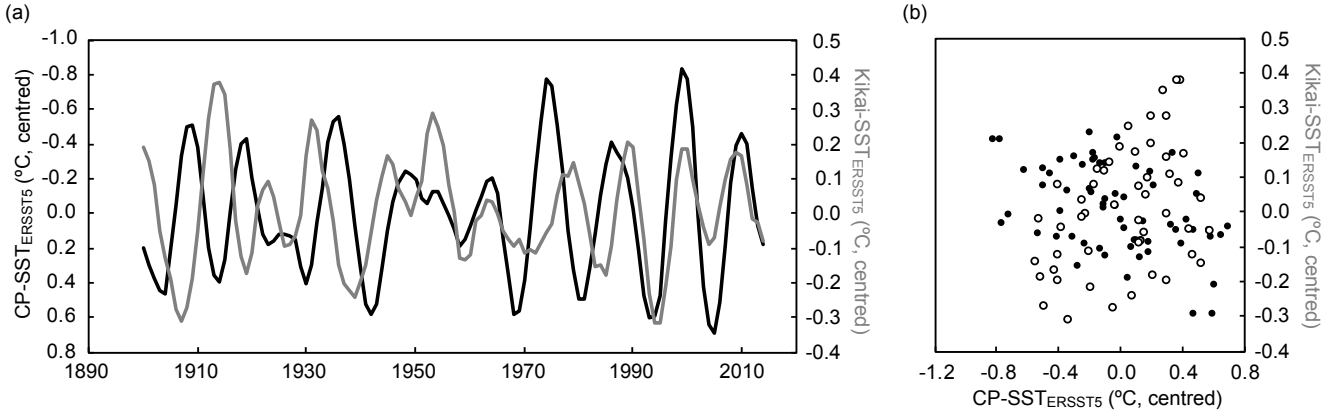

Figure A13. Comparison of time series between instrumental temperature records from the regions of the CP and Kikai Island.

(a) Time series of CP-SST$_{ERSST5}$ (Huang et al., 2017, in black) and Kikai-SST$_{ERSST5}$ (Huang et al., 2017, in grey) for the period 1900–2014 CE. (b) Scatter plot corresponding to (a). Open-circle plots are data for the period 1900–1949 CE. Closed-circle plots are data for the period 1950–2014 CE.

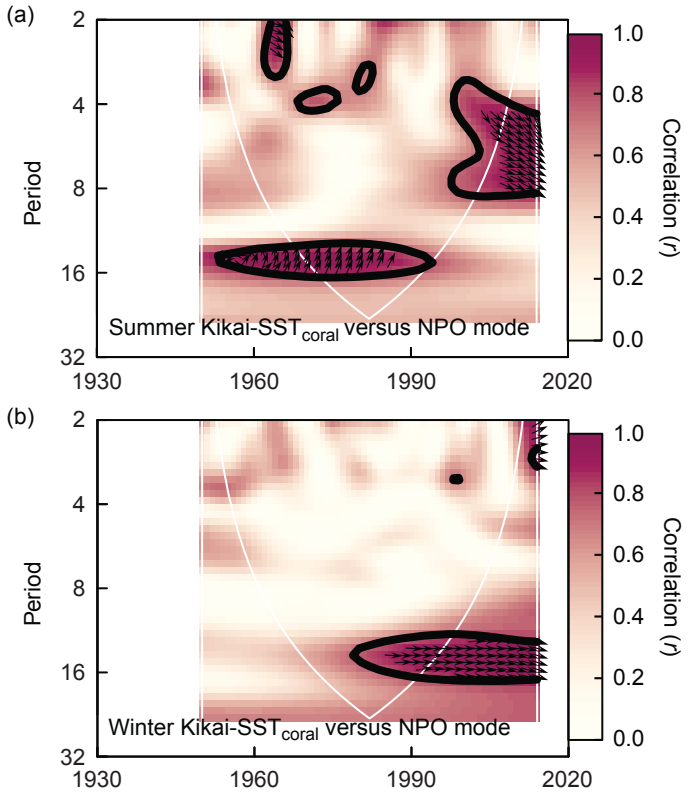

Figure A14. Cross-wavelet coherence analysis between Kikai-SST$_{coral}$ and NPO variability.

(a) Cross-wavelet coherence between Summer Kikai-SST$_{coral}$ time series and NPO variability (December–February) for the period 1950–2014 CE. The NPO dataset is calculated from the Hadley Centre Sea Level Pressure dataset (HadSLP2r, Allan and Ansell, 2006; 30–65° N, 160° E–140° W) using the empirical orthogonal function method of Trenberth and Hurrell (1994) at KNMI Climate Explorer. Regions of significant coherence (*p*-values < 0.1) are outlined by solid contours. Arrows indicate the phase relationship. (b) Same as (a), but between Winter Kikai-SST$_{coral}$ time series and NPO variability (December–February).

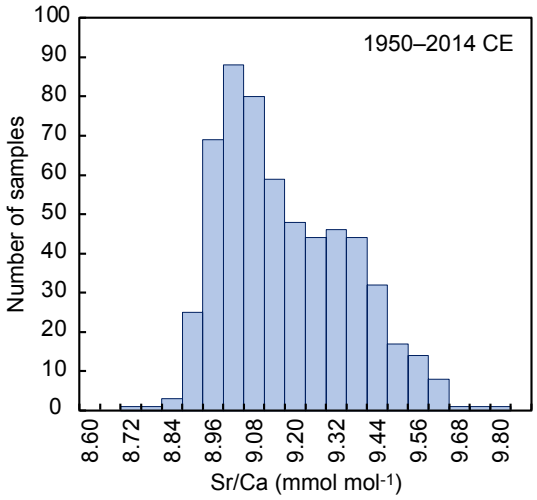

Figure A15. Histogram of Kikai-coral Sr/Ca record from 1950 to 2014 CE.

The x-axis interval is 0.06 mmol mol^{-1}, which corresponds to approximately 1 ºC (Corrège, 2006). Higher (lower) Sr/Ca values indicate cooler (warmer) temperatures.

Data availability

Archiving of all data is underway, and it will be made available at the KIKAI Coral Reef Science Institute data repository (https://coralogy.kikaireefs.org/) and the PANGAEA open-access library (https://www.pangaea.de/) immediately after this manuscript is accepted.

Author contributions

S.I. conceptualised the study and designed it with T.K.W and T.W. Coral samples were collected by S.I., A.Y., T.K., and T.W. Skeletal geochemical analysis was performed by S.I., and U–Th dating was performed by T.K.W. and C.–C.S. Diagenesis screening was conducted by S.I. (powder X-ray diffraction and scanning electron microscopy) and T.K. (scanning electron microscopy). Statistical analyses were conducted by S.I. and T.K.W. The first draft of the manuscript was written by S.I., and all authors contributed to further conceptual and content development, as well as the interpretation of the data.

Competing interests

The authors declare that they have no conflict of interest.

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