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A skeletal Sr/Ca record preserved in *Dipsastraea* (*Favia*) *speciosa* and implications for coral Sr/Ca thermometry in mid-latitude regions

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[1] A core (900 mm long) of the scleractinian coral *Dipsastraea* (*Favia*) *speciosa* was collected from Iki Island (~33°48′N), Japan, one of the highest latitude coral reefs known to exist at present, where winter monthly mean sea surface temperature (SST) drops to 13°C. The Sr/Ca profile was constructed using a bulk sampling method for the uppermost 280 mm interval of the core, which grew between 1966 and 2007, to test whether it could act as a suitable proxy for SST in a harsh environmental setting where reef-building coral do not usually survive. The Sr/Ca-SST relationship derived from the annual Sr/Ca and SST extremes predicted the observed monthly averaged summer SST extremes within an error range of ± 1.1°C (1 s.d., $n = 40$). The obtained Sr/Ca-SST calibration was also found to be valid for subtropical *Dipsastraea* (*Favia*) corals, proving its broad applicability. However, low-amplitude winter peaks were observed in the slow-growing intervals, which we confirmed (using individual spot analysis along a continuous growth line) result from the mixing of theca grown at different times. Our bulk sampling approach, across multiple growth lines in the skeleton of *D.* (*F.*) *speciosa*, led to the mixing of asynchronous skeletal part. At the study site, *D.* (*F.*) *speciosa* grows continuously, even during the cold season, suggesting that the skeletal Sr/Ca obtained from specimens of *D.* (*F.*) *speciosa* can be used as an SST proxy in the northwest Pacific marginal seas.

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1. Introduction

[2] Reef-building corals, especially those that form massive coral colonies, preserve climate records that may extend over many centuries [e.g., *Pätzold*, 1992; *Quinn*, 1993; *Goodkin et al.*, 2008]. Fossil corals can extend these paleoclimate records further geologic past [e.g., *Gagan et al.*, 1998; *Allison et al.*, 2005; *Mishima et al.*, 2009; *Watanabe et al.*, 2011]. However, coral-derived long-term climate reconstructions that extend beyond the period covered by instrumental records are scarce in middle-latitude regions north of 30° latitude due to the low winter temperatures there. An exception is found in Bermuda (32°N) on the western margin of the Atlantic Ocean, where the warm Gulf Stream allows stable and long-term growth of the brain coral *Diploria labyrinthiformis*, and this has been used to reconstruct multi-century paleoclimatic data [e.g., *Nozaki et al.*, 1978; *Goodkin et al.*, 2005, 2008].

[3] Similarly, the East Asian marginal seas on the western boundary of the Pacific are influenced by the Kuroshio Warm Current, and also provide an unusual environment for coral distribution. In the Korea Strait, the Tsushima Warm Current, a northward flowing tributary of the Kuroshio Warm Current, pushes the northern limit of coral distribution into the temperate region (Figure 1). In this special setting, corals belonging family Merulinidae (following the classification of *Budd et al.* [2012]; previously belongs to the family Faviidae in *Veron* [2000]), such as *Cyphastrea*, *Dipsastraea* (*Favia* in *Veron* [2000]'s classification), *Favites*, *Goniastrea*, and *Platygyra* sp., are widely distributed up to 35°N [*Yamano et al.*, 2001, 2004, 2011, 2012; *Sugihara and Yamano*, 2004] (Figure 1). In particular, *Dipsastraea* (*Favia*) is the most common genus at ~34°N, and it builds large living colonies up to around 1 m in height. These corals, predominantly *Dipsastraea* (*Favia*), also comprise a major coral component of the reef structures that have developed in the coastal zones of Iki Island

(~33°48′N) and Tsushima Island (~34°30′N), where the *Dipsastraea* (*Favia*) fossils extend the maximum age to ~2800 (555 cm in height) and ~4300 years B.P. (525 cm in height), respectively [*Yamano et al.*, 2012]. Therefore, the *Dipsastraea* (*Favia*) colonies and fossils have the potential to act as paleoclimatic and paleoceanographic archives for this temperate setting.

[4] *Dipsastraea* coral skeletons have been shown to be reliable recorders of environmental conditions in tropical to subtropical regions based on their preserved stable oxygen isotope composition in *Weber and Woodhead* [1972] and Sr/Ca ratios [*Mishima et al.*, 2009]. However, *Dipsastraea* (*Favia*) in the Korea Strait is exposed to a harsh environment characterized by large seasonal temperature fluctuations and, more importantly, low winter temperatures falling down to 13°C. These environmental conditions cast doubt on its appropriateness as an environmental archive, and consequently, its reliability as an environmental recorder needs to be verified. Previous studies have found that such environmental conditions may restrict the continuous growth of coral, and make skeletal geochemistry less reliable [*Fallon et al.*, 1999; *Montagna et al.*, 2007]. For instance, *Montagna et al.* [2007] suggested that a *Cladocora caespitosa* stopped skeletal growth during the cold season in the Mediterranean Sea. Other field surveys and laboratory culture experiments have also documented the absence of coral reef and/or the cessation of calcification in some species at temperatures below 16°C–18°C [*Jacques et al.*, 1977; *Walker et al.*, 1982; *Burns*, 1985; *Lough and Barnes*, 2000]. Thus, these studies suggest the presence of a low-temperature limit for coral growth (hereafter referred to as the threshold temperature). The monthly sea surface temperature (SST) in the Korea Strait drops to 13°C during the winter, and this indicates the possibility of growth disturbance in the strait during the cold season. In addition, the effect of growth disturbance can be
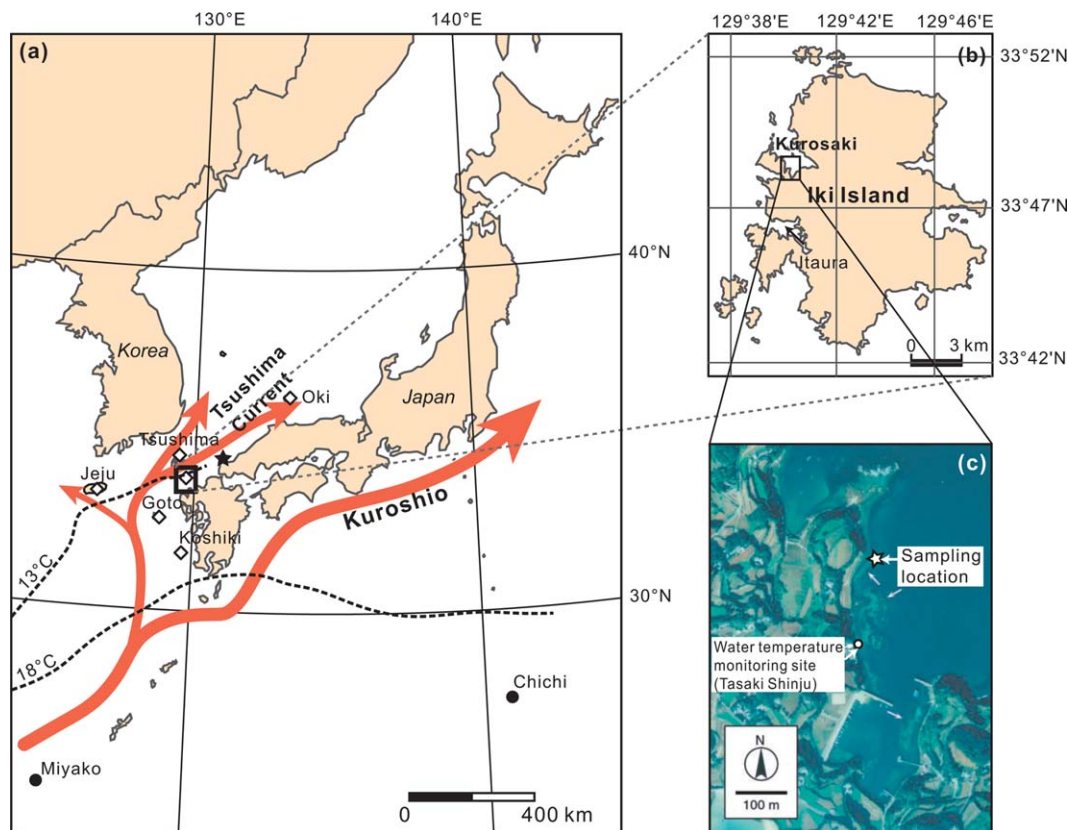
Figure 1. (a) Regional map of the study area showing locations where Faviid coral communities have been reported (open diamonds) and pathways of the Kuroshio and Tsushima currents. Contours (dashed lines) are isotherms of monthly average SST for the coldest month [*Yamano et al.*, 2001]. Solid circles show locations of Chichi Island and Miyako Island, where modern and fossil *Dipsastraea (Favia)* corals were studied by *Mishima et al.* [2009]. The location where optimal interpolation temperature was obtained by *Minobe et al.* [2004] is marked with a filled star (see text). (b) Map of Iki Island. Coral communities are distributed in Kurosaki and Itaura bays, on the western side of the island. The coral samples analyzed in this study were collected in Kurosaki Bay. (c) Locations of the sampling (open star) and monitoring sites (open circle). Modified after *Yamano et al.* [2001].

carried over to the geochemical signals of the subsequent summer in *Porites* [*Suzuki et al.*, 2003; *Omata et al.*, 2006]. Therefore, these two aspects (i.e., the possibility of growth stopping during the cold season, and its effect on the geochemical signal of the following summer season) must be clarified before *Dipsastraea (Favia)* can be used as an environmental archive in this particular setting.

[5] This study aims to test the Sr/Ca thermometry of *Dipsastraea (Favia) speciosa* in the Korea Strait in an attempt to reconstruct the past climatic record using a large living colony and fossils. We collected a 900 mm long core from a living *D. (F.) speciosa* coral colony on Iki Island, Japan (Figure 1). Sr/Ca in the uppermost 280 mm of the core was measured by bulk sampling and, in part, by individual spot analysis. Our coring site is close to that of *Yamano*

et al. [2001, 2012]; thus, this study is the first step in the reconstruction of the long-term climatic history of the Korea Strait. We also address the problems of the validity and implications of winter Sr/Ca records derived from *D. (F.) speciosa* that lives under environmental conditions that are unfavorable for coral survival. In addition, we examine the applicability of our Sr/Ca thermometry of *D. (F.) speciosa* to subtropical regions.

2. Materials and Methods

[6] Iki Island (33°48′N, 129°39′E), is located in the Tsushima Strait, the eastern channel of the Korea Strait (Figure 1). Mean monthly SSTs varied between 13.3°C (February) and 27.0°C (August) during the period 1986–2007. The island

is warmer than other areas at a similar latitude due to the direct influence of the Tsushima Warm Current, as indicated by the 13°C isotherm line in the coldest month (Figure 1a).

[7] In 2007, a 900 mm long core was retrieved through a vertical axis of a living coral colony of *D. (F.) speciosa*, which was part of a reef described by *Yamano et al.* [2001, 2012] at a water depth of around 2 m in Kurosaki Bay (Figures 1b and 1c). The in situ SST data (hereafter called Kurosaki SST) are available from 1986 to 2007 (calibration period) and were measured daily by the Tasaki Shinju Company at a site about 200 m south of the coring site (Figure 1c). The monthly averaged SSTs from this data set were used to establish the Sr/Ca-SST relationship. The potential error associated with the use of daily data to generate a monthly averaged SST is less than 0.2°C when compared with data gathered every 30 min (K. Sugihara, personal communication, 2010). Additional SST data, derived from an optimal interpolation method, are available at a monthly interval from 1951 to 1996 from the easternmost part of the Tsushima Strait (Figure 1a; spatial smoothing of a 0.5° × 0.5° grid centered at 131°E, 34.5°N at the surface) [*Minobe et al.*, 2004]. The latter data (hereafter called OI SST) show a good linear correlation ($r = 0.98$, $p < 0.0001$, $n = 132$) with the Kurosaki SSTs for the overlapping period between 1986 and 1996, but the monthly average is offset by approximately $+0.3 \pm 0.8$°C (1 s.d.) from the Kurosaki SSTs. The OI SSTs were used to verify the reliability of the Sr/Ca-derived SSTs for the period 1966–1986 (verification period), for which measured SSTs are unavailable from Kurosaki Bay.

[8] The uppermost 280 mm interval of the coral core was subjected to wet analysis to determine the Sr/Ca profile. The core was sliced into 10 mm sections, cleaned in an ultrasonic bath with Milli-Q water, and then dried in an oven at 50°C. An X-ray radiograph was obtained for each section using SOFTEX radiographer M-60, and the image was used to select a single continuous corallite from the section, which was then isolated for analysis (Figure 2a). Mixing of the geochemical signal from different skeletal elements can be problematic when using corals with large polyps [e.g., *Watanabe et al.*, 2002, 2003]. To minimize this problem, only theca walls were subjected to analysis after removing other internal skeletal structures using a dental drill.

[9] A freezing microtome sampling method was used to subsample the specimen, due to its porous and fragile skeletal texture [e.g., *Watanabe and Oba*, 1999; *Shimamura et al.*, 2005]. The isolated theca was cut perpendicular to the growth axis to fit into the microtome (Bright Instrument OTF 5000 Cryostat) with dimensions of approximately 5 mm (width) × 2 mm (thickness) × 50 mm (length). The theca of *D. (F.) speciosa* consists of a series of thickened septa, each of which can be seen clearly as a linear projection outside and inside of theca and represents a continuous growth line. A theca stick of ∼5 mm wide includes 6–7 septa in general. Each section was buried in an ice block, shaved into powder by a steel blade of microtome in the cryostat maintained at −30°C, and freeze-dried to remove water. We intended to collect the shaved subsamples at intervals of 200 μm; however, as the edge of the blade get often blunt during the procedure, it was difficult to maintain a constant sampling interval. As a result of this limitation, the sample distance in each sample stick was estimated based on the number of subsamples and the length of each section. This approach gives the average extension rate of each section, but does not allow for the determination of the annual linear extension for a particular year. The average sampling interval was estimated to be about 140 μm.

[10] Subsamples were treated with 4 m*M* HNO₃ and rinsed three times with Milli-Q water to remove potential contaminants and inorganically precipitated aragonite, as described in *Watanabe et al.* [2001]. The subsamples were then dissolved and diluted to give a final calcium concentration of around 10 ppm to minimize the matrix effect with known average concentrations of Ca and Sr in the coral aragonite and approximate sample weights. Concentrations of Ca and Sr were measured from the spectral lines at 407.776 and 317.933 nm, respectively, using an inductively coupled plasma-optical emission spectrophotometer (ICP-OES) (Perkin-Elmer Optima 3300 DV) at the Korea Institute of Ocean Science and Technology, Ansan, Korea. Every third or fourth subsample was analyzed for Sr/Ca, providing about a monthly resolution. Additional analysis was performed on the section between 150 and 191 mm to test whether this analytical resolution is sufficient to resolve complete seasonal Sr/Ca amplitudes (see below). Based on the initial analytical results with a monthly resolution, all of the omitted subsamples around the annual maxima and minima of Sr/Ca were analyzed for this specific interval. Instrumental drift was corrected for according to *Schrag* [1999]. The analytical error of Sr/Ca, based on
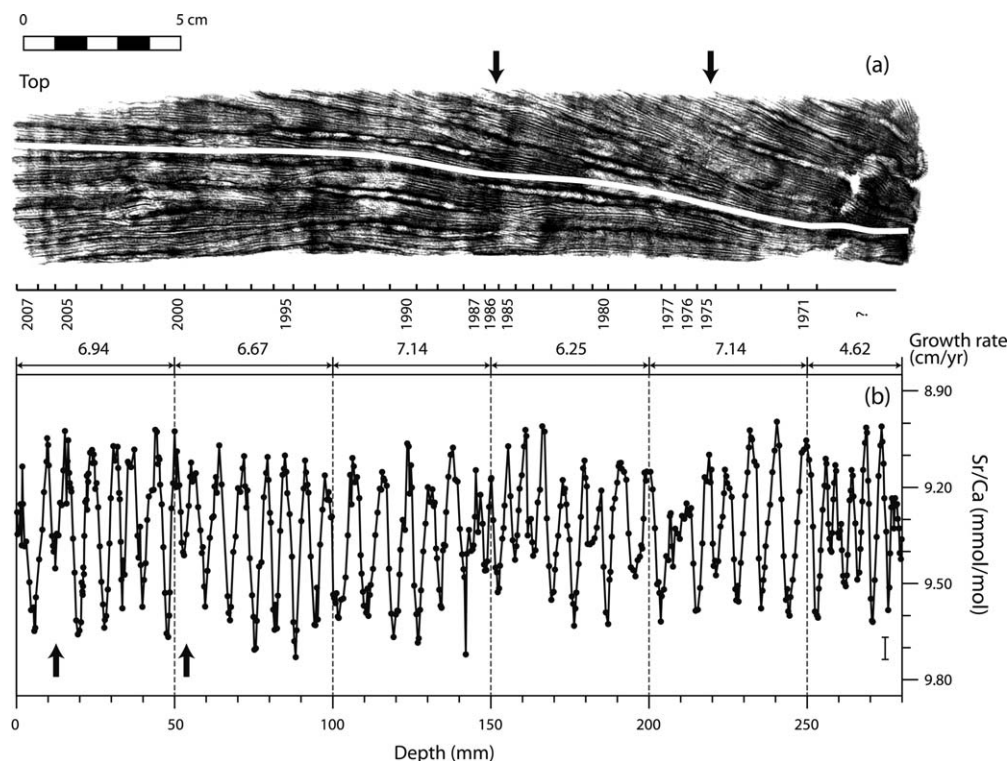
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Figure 2. (a) X-ray radiograph of the *D. (F.) speciosa* specimen showing the corresponding growing years and transect for microsampling (solid white line). The points of corallite bifurcation are marked by arrows. (b) Plot of Sr/Ca ratios determined by ICP-OES against distance from the top of the core. The isolated corallite was cut into six sections, which are marked by vertical dashed lines. The average growth rate of each section is given at the top (see section 2 for details). Winter extreme values from the periods 2005–2006 and 1999–2000, excluded from the calibration of Sr/Ca-SST relationship, are marked by arrows.

replicate measurements of the coral standard JCp-1, provided by the Geological Survey of Japan [*Okai et al.*, 2002], was 0.4% (1 s.d., $n = 1126$).

[11] The bulk sampling method used in this study may induce lateral mixing of theca that had grown at different times, which results in the dampening of amplitudes in the slowly growing parts of the coral. We evaluated this possibility using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) for the 150–191 mm interval, which showed low-amplitude winter peaks in the Sr/Ca determined with ICP-OES with a resolution of 0.14 mm per sample. For this, the specimen was mounted in epoxy resin and polished along a single septum, which represents a single continuous growth line. The ^{88}Sr and ^{44}Ca content of the selected septum was then analyzed with a New Wave UP 213 Laser Ablation System and Thermo Elemental X7 ICP-MS at the Korea Basic Science Institute at an interval of 150 μm with an analytical spot size of 40 μm. The data were collected in time-resolved mode, with the coral data being

bracketed by scans of 60 s on a National Institute of Standards and Technology (NIST) standard reference material (SRM) 612 standard [*Pearce et al.*, 1997] and 30 s of instrumental background. As carbonate standards that are chemically homogenous at the 1% level are not available, the absolute concentrations of Ca and Sr could not be obtained. Instead, we normalized the Sr/Ca counts (hereafter normalized Sr/Ca) from the LA-ICP-MS results to the most prominent peaks, 1984 summer and 1981–1982 winter extremes, produced from ICP-OES result.

3. Results

[12] The X-ray radiograph image of the core section revealed annual density bands and did not show any anomalous density patches indicative of diagenetic alteration (Figure 2a). The Sr/Ca values measured using ICP-OES vary from 9.00 to 9.73 mmol/mol (9.33 mmol/mol on average), with

lower and higher extremes occurring in summer and winter, respectively (Figure 2b). The analyzed topmost 280 mm interval of the living coral core was estimated to have grown over the past 42 years, from 1966 to 2007, based on the growth bands on the X-ray radiograph and the annual Sr/Ca cycles (Figure 2). The mean annual growth rate was calculated to be 6.6 ± 1.1 mm/yr (1 s.d., $n = 42$).

[13] Normalized Sr/Ca values obtained using LA-ICP-MS from the 150–191 mm section revealed a consistent and regular shape of the winter peaks when compared with the equivalents obtained using ICP-OES (Figure 3). Although the counts were not quantitatively converted to the absolute concentration, the normalized Sr/Ca values exhibit clear annual cycles and are positively correlated with those from the ICP-OES.

4. Discussion

4.1. Sr/Ca-SST Relationship

[14] The determined bulk Sr/Ca was negatively correlated with the observed temperature. During the monitoring period from 1987 to 2007, Sr/Ca variation does not show abnormal signals caused by a breakdown of temperature-dependent Sr and Ca uptake as observed in the Sr/Ca profiles of *McCulloch et al.* [1994] and *Marshall and McCulloch* [2002]. Therefore, the temperature dependence of the Sr/Ca was estimated from a linear regression of winter and summer Sr/Ca extremes with the corresponding monthly averaged annual SST extremes (Kurosaki SST), following *McConnaughey* [1989] and *Gagan et al.* [1998]:

[15] Sr/Ca (mmol/mol) = 10.184 (± 0.053) $- 0.0408$ (± 0.002) $\times$ SST (°C) (2σ; 95% confidence level, $r^2 = 0.97$, $n = 38$, $p < 0.0001$) (Figure 4)

[16] The winter Sr/Ca extremes in 2005–2006 and 1999–2000 were very low compared with other winter extremes, despite the corresponding temperatures being similar to the other years (Figure 4). These data clearly deviate from the regression trend, and thus were excluded from the regression. The temperature dependence (-0.0408 mmol/mol/°C) of the Sr/Ca obtained in this study is somewhat greater than the value of -0.032 reported from a modern subtropical *D. (F.) speciosa* by *Mishima et al.* [2009]. Although the slope is gentler than the averages reported for *Porites* (-0.0607) and non-*Porites* genera (-0.0596) by

Corrège [2006] (Figure 4), it is similar to the slopes of other faviid corals having large corallite such as *Diploria* (-0.036 to -0.048) [*Cardinal et al.*, 2001; *Goodkin et al.*, 2005; *Hetzinger et al.*, 2006] and *Montastrea* (-0.028 to -0.047) [*Swart et al.*, 2002; *Smith et al.*, 2006], mainly reported in the Atlantic.

4.2. Accuracy of Sr/Ca Thermometry

[17] Using the derived Sr/Ca-SST relationship, the proxy temperatures were reconstructed and compared with the observations (Kurosaki and OI SSTs) over the entire study period (Figure 5). The range of reconstructed annual maximum SST, varying from 24.1°C to 28.5°C, agrees well with the observed summer SST record (24.1°C–28.7°C) for the calibration period (1987–2007) (Figure 5). The standard error of the residuals of the summer SSTs is ± 1.1°C (1 s.d., $r = 0.63$, $n = 21$). The good predictability of the Sr/Ca thermometry suggests that SST is the main controlling factor of the skeletal Sr/Ca ratio during the summer. Similarly, the winter Sr/Ca extremes yield reconstructed SSTs ranging from 11.1°C to 15°C for the same period (excepting the two data points excluded from the calibration), which is similar to the range of measured winter SST extremes that vary between 12.2°C and 14.4°C. However, the winter Sr/Ca extremes form a circular cluster in the SST-Sr/Ca scatterplot, and do not show any meaningful correlation against the measured winter SST extremes ($r = 0.1$, $n = 19$, $p = 0.68$) (Figure 4). It should be noted that the measured winter extreme temperatures vary within a narrow range of ± 1.1°C (1 s.d.), exactly the same as the error range found in the reconstructed summer SSTs. The precision of the Sr/Ca thermometry may be too low (as a result of the limitations imposed by the bulk subsampling method used here) to resolve small interannual variations in winter temperatures.

[18] To verify the applicability of Sr/Ca thermometry as a long-term climate recorder, the Sr/Ca-derived summer extreme SSTs were compared with the OI SSTs between 1966 and 1986 (verification period) (Figure 5). The reconstructed SSTs show generally good agreements with the summer OI SSTs, except for the summers of 1976 and 1977, which do not show clear seasonality. Excluding these 2 years, the standard error of the residuals between Sr/Ca-derived and OI SSTs is 0.7 ± 1.1°C (1 s.d., $r = 0.71$, $n = 18$, $p < 0.001$). This offset of 0.7°C is probably attributable to the
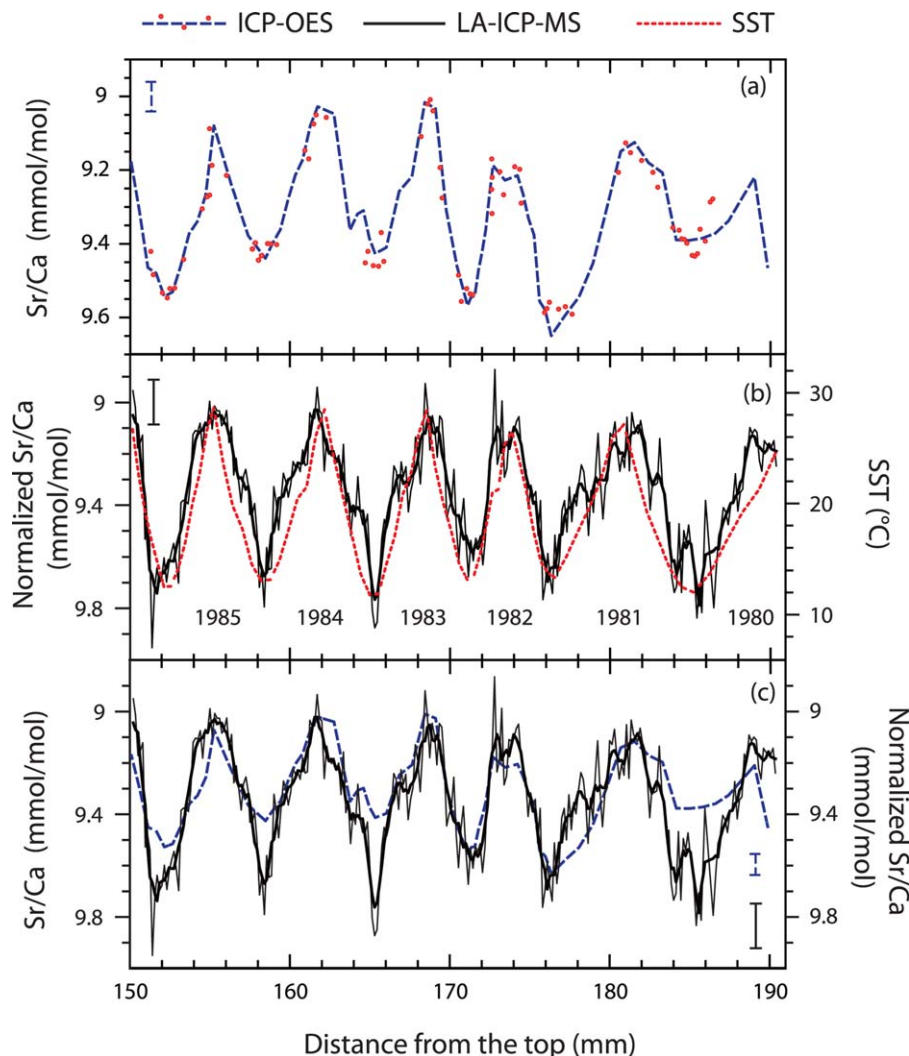
Figure 3. Combined analytical results from the core section between 150 and 191 mm. (a) Sr/Ca of every third-sample and fourth-sample analysis are given as a blue dashed line, and the results for samples omitted from the initial analysis in the peak areas are given as red solid circles, (b) comparison of normalized Sr/Ca measured using LA-ICP-MS with OI SST records (red dotted line), and (c) comparison of normalized Sr/Ca measured using LA-ICP-MS with those measured using ICP-OES (blue dashed line). Thin and thick solid lines in Figure 3b and 3c represent all results of the LA-ICP-MS analysis and five-point moving average, respectively. The LA-ICP-MS data were normalized to the ICP-OES results of the summer 1984 and winter 1981–1982 peaks, which are the most prominent peaks in this interval.

differing origins of the data sets, and the distance between the sites at which samples and OI SST data were collected (see Figure 1). The reconstructed summer extreme SSTs show excellent agreement with instrumental records for the 42 years of the study period (Figure 5), verifying their value as a long-term climate proxy for summer SSTs. The cause of the weak summer peaks in 1976 and 1977 is not clear at present. The branch bifurcation observed during the 1974−1975 period (Figure 2), and related physiological stress,

could explain the subsequent weak peaks in 1976 and 1977, as previously reported in the *Porites* by *Alibert and Kinsley* [2008] and *DeLong et al.* [2013]. However, another bifurcation occurred in 1985−1986, but had no recognizable effect on summer Sr/Ca in the following years. Such variability makes it difficult to evaluate the effect of branch bifurcation on the Sr/Ca in our specimen.

[19] In contrast to the results from the calibration period, the reconstructed winter SST extremes during the verification period before 1986
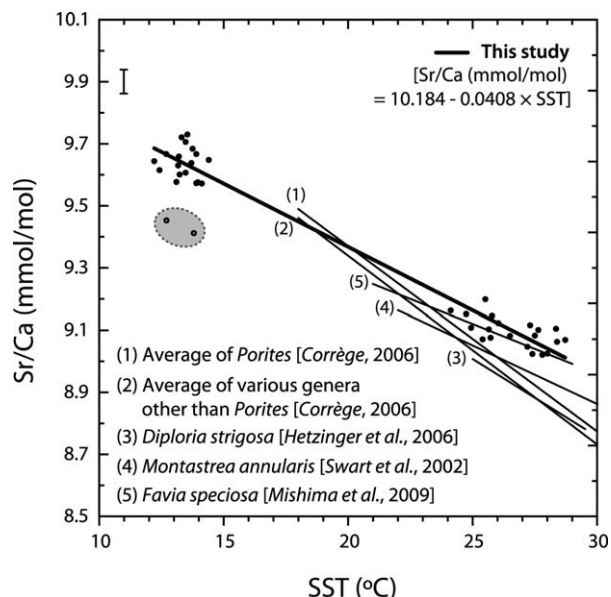
Figure 4. Plot of winter and summer Sr/Ca ratio extremes against the corresponding monthly averaged annual SST extremes (Kurosaki SSTs) from 1987 to 2007 (filled circles) with the linear fit of our data set (thick solid line). For comparison, equations reported in previous studies are also presented. Data from the winters of 2005–2006 and 1999–2000, which were excluded from the regression, are shown as open circles.

show large discrepancies ($r = 0.58$; average of residuals $= -3.0 \pm 2.6°C$ (1 s.d.), $n = 20$, $p < 0.001$) from the OI SSTs beyond the estimated method

error of $\pm 1.1°C$. Given that irregular peaks are observed only in winter, it seems reasonable to attribute these larger discrepancies to a response to winter thermal stress. Interestingly, however, such irregularities are mostly found in the winters of 1974–1986 and 1968–1970. Such inconsistent response of the geochemical signal to low-temperature stress should be examined in more detail, because an improved understanding of coral behavior during the winter will be necessary if we are to establish Sr/Ca thermometry in temperate regions.

4.3. Cause of Low-Amplitude Peaks in the Winters of 1980–1986 and 1968–1970

4.3.1. Uneven Calcifying Surface

[20] The low-amplitude Sr/Ca peaks recorded during the winters of 1980–1986 and 1968–1970 may have resulted from the incomplete recovery of the seasonal cycles due to the low resolution of the analytical method (every third or fourth subsample) used in this study. To investigate this possibility, we determined the Sr/Ca of samples omitted from the initial analysis in the peak areas of the 150–191 mm section that contained low-amplitude Sr/Ca peaks (Figure 3a). These additional Sr/Ca data did not improve the peak shape; i.e., there was no difference in peak height with or without the additional data, proving that the low-amplitude peaks were not caused by the analysis of
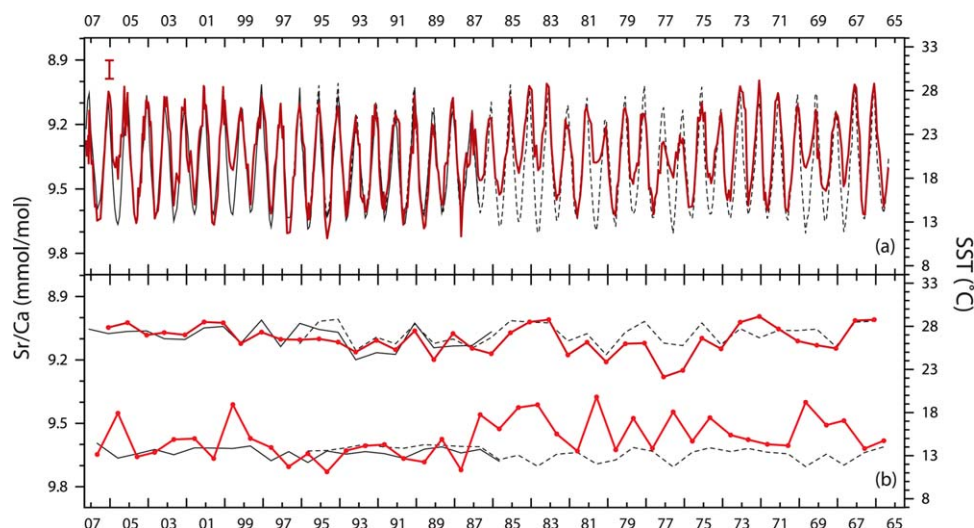

Figure 5. (a) Sr/Ca ratios and reconstructed SSTs plotted against time (thick solid line) together with the observed SSTs (Kurosaki SST: thin solid line; OI SST: thin dashed line). The distance was converted to time by peak-to-peak matching using AnalySeries software [*Paillard et al.*, 1996]. Sr/Ca records are translated into temperature using the Sr/Ca-SST relationship established in Figure 4. (b) Comparison of reconstructed annual extreme SSTs (thick solid line) with the corresponding observed SSTs. SST records in Figures 5a and 5b are either from about 200 m south of the core location (1986–2007; thin solid line), or from the easternmost Tsushima Strait (OI SST, 1966–1986; dashed line).

discontinuous samples. It is interesting to note that the low-amplitude winter peaks mostly occur in sections with low average growth rates: 6.25 mm/yr in the 150–200 mm interval (1978–1986) and 4.62 mm/yr in the 250–280 mm interval (1966–1971) (Figure 2b). This suggests that the possibility that the low-amplitude winter peaks are related to low linear extension rates. Variable extension rates on the calcifying surface and the mixing of theca that had grown after a slight time gap (asynchronous skeletal parts) offer a plausible explanation for the low amplitudes of winter peaks preserved within the slow-growing intervals [e.g., *Giry et al.*, 2010].

[21] The diameter of a corallite in a *D. (F.) speciosa* specimen (9–11 mm) is larger than its annual extension rate (6.6 ± 1.1 mm) at our study site; therefore, calcification surface is often uneven and not perpendicular to the major growth axis and thus calcification may not proceed in parallel through a calcifying horizon. Due to the complexity of the internal structure of corallite and concerns regarding the mixing of asynchronous theca, the sampling strategy is an important consideration when dealing with large polyp corals [e.g., *Leder et al.*, 1996; *Watanabe et al.*, 2002, 2003; *Smith et al.*, 2006; *Giry et al.*, 2010]. Accordingly, most studies use a subsampling strategy collecting a continuous sample along a small area of theca wall [e.g., *Giry et al.*, 2010] (0.6 mm wide × 2 mm deep). However, the *D. (F.) speciosa* that inhabits our study site is fragile and porous, and it is not appropriate to use a milling machine for subsampling. Specifically, the *D. (F.) speciosa* skeleton from the study site is less dense (0.9–1.1 g/cm³) than its subtropical equivalent (1.5–1.7 g/cm³) [*Nakata et al.*, 2013]. For this reason, we removed the internal structure of the corallite and then shaved off the 5 mm wide stick using a freezing microtome method. The 5 mm wide theca stick includes 6–7 septa, each of which represents a single continuous growth line. Thus, with the sampling strategy adopted in this study, the time-averaging effect at the sampling horizon due to uneven linear extension can be significant, especially during the winter periods of slow extension.

[22] To obtain further verification of the cause of low-amplitude winter peaks, the slow-growing section (150–191 mm) was subjected to individual spot analysis by LA-ICP-MS along a single septum. This approach eliminates the possibility of the skeletal mixing of different growth horizons. In support of our reasoning, winter peak irregularities were not observed in the results of the laser ablation analysis (Figures 3b and 3c). Instead, the extreme values of the peaks are remarkably well matched with those of the SST record ($r = -0.79$, $n = 6$, $p = 0.06$) suggesting that a more accurate Sr/Ca-derived SST record can be obtained when the analysis is carried out along a single growth line.

[23] From the comparison of these two analytical results, we conclude that the inaccuracy of Sr/Ca-derived winter SSTs over the periods 1980–1986 and 1968–1970 resulted from mixing of theca that grew at slightly different times. The current sampling method seems not to reduce the accuracy of Sr/Ca thermometry in summer, thereby confirming its value as a proxy for summer SSTs. During summer, the skeletal extension rate was high enough to mitigate the effect of uneven linear extension and subsequent mixing. This interpretation is supported by the arched shape (broad summer and narrow winter peaks) of the Sr/Ca curve from the laser ablation analysis, which is not evident in the bulk analysis results. Such a pattern of arch-shaped peaks indicates faster growth in summer than in winter [e.g., *Barnes et al.*, 1995; *Fallon et al.*, 1999; *Montagna et al.*, 2007]. Nevertheless, we recommend sampling along a narrow area for bulk analysis of *D. (F.) speciosa* to minimize the mixing of asynchronous skeletal parts in slowly grown interval to ensure complete recovery of seasonal cycles.

4.3.2. Cessation of *Growth*

[24] Inconsistent winter peaks lacking correlation with observed SSTs have been reported in previous studies dealing with temperate corals [*Fallon et al.*, 1999; *Montagna et al.*, 2007]. These studies attributed the irregular winter peaks to growth failure of the coral skeletons due to thermal stress below a certain threshold temperature. This interpretation was essentially based on studies that reported: (1) a general lack of coral reefs in areas where the temperature falls below 15°C–16°C [*Walker et al.*, 1982; *Burns*, 1985] and (2) the absence of net $CaCO_3$ accretion below 15°C in *Astrangia danae* [*Jacques et al.*, 1977], or 17.5°C in *Porites* sp. [*Lough and Barnes*, 2000] in laboratory experiments.

[25] However, the presence of a threshold temperature, and the possibility that growth stops in winter, must be carefully examined for temperate *Dipsastraea* (*Favia*) corals because the tolerance of reef coral to thermal stress is highly variable and is dependent on the thermal adaptability of the host corals and, more critically, on the genotype of the algal symbionts [*Saxby et al.*, 2003; *Rowan*, 2004; *Berkelmanns and van Oppen*, 2006;

LaJeunesse et al., 2010; *Kemp et al.*, 2011]. For example, *Porites* and *Montastrea*, the common reef-building corals in Pacific and Atlantic, respectively, often suffer bleaching and mortality in the tropics due to low-temperature stress [*Hudson et al.*, 1976; *Kemp et al.*, 2011]. In contrast, *Porites* on the mid-latitude southern coast of Japan can endure long cold winters below 16°C [*Fallon et al.*, 1999; *Omata et al.*, 2006]. *Dipsastraea* in the Korea Strait region also appears to be able to tolerate low-winter temperatures, judging from its ability to form reef structures since around 4300 years B.P. [*Yamano et al.*, 2012]. From this point of view, the response of temperate corals to periodic exposure to low temperatures appears to differ to that of their tropical equivalents exposed to a sudden invasion of thermal stress. Therefore, it seems unlikely that a universal temperature limit exists for coral growth that can be applied to all reef corals [*Coles et al.*, 1976; *Coles and Fadlallah*, 1991; *Kleypas et al.*, 1999].

[26] Our Sr/Ca results obtained from the laser ablation technique do not support the possibility of complete cessation of skeletal growth during the cold season. The winter extremes identified from the individual spot analyses show a fair negative relationship with SST (Figure 3b), suggesting that our specimen recorded winter SSTs in the form of varying geochemical signatures. In addition, an unexpected geochemical signal, such as $\delta^{18}O$ and Sr/Ca that is significantly lower or higher than the usual value, can be an indicator of growth failure in tropical and temperate corals [e.g., *Fallon et al.*, 1999; *Marshall and McCulloch*, 2002; *Omata et al.*, 2006; *Montagna et al.*, 2007]. However, the winter Sr/Ca peaks obtained from our bulk analysis are consistent with the observed SSTs, except for those from the winters of 1980–1986 and 1968–1970, which we have demonstrated are the result of the mixing of asynchronous theca in slowly grown intervals (Figure 4). Taking account of the similar winter temperatures (±1.1°C, 1 s.d.) through the monitoring period, low-temperature stress and resultant growth failure can be discounted as a possible cause of the low-amplitude peaks recorded in the winters of these two periods. The threshold temperature, if any, for the temperate *D. (F.) speciosa* may be lower than the coldest winter temperatures recognized in the study area.

4.4. Applicability of Skeletal Sr/Ca Thermometry Using *D. (F.) speciosa*

[27] Sr/Ca ratios obtained from *D. (F.) speciosa* skeletons have been investigated previously to test their suitability as a paleo-SST proxy in subtropical [*Mishima et al.*, 2009] and mid-latitude regions [*Hyeong et al.*, 2008]. In both previous studies, the presence of annual growth banding and seasonal fluctuations in Sr/Ca was confirmed to resemble those seen in SST time series. In particular, *Mishima et al.* [2009] tried to reconstruct SSTs around Chichi Island (27°4′N, Figure 1a), Japan using fossil *Dipsastraea* sp. from 16 ka, based on Sr/Ca values obtained from modern *D. (F.) speciosa* collected near Miyako Island (24°43′N, Figure 1a). However, they were unable to establish a clear relationship between Sr/Ca and SST. The Sr/Ca-SST relationship derived by *Mishima et al.* [2009] resulted in a very shallow slope (−0.032 mmol/mol/°C) and unrealistically reconstructed SSTs at 16 ka. For this reason, they used the average of all the reported slope values, a temperature dependence of −0.06 mmol/mol/°C, to reconstruct the SST at 16 ka from the fossil *Dipsastraea* sp.

[28] To test the potential and wider applicability of *D. (F.) speciosa* as a long-term paleoceanographic recorder in the northwestern Pacific marginal seas, the regression obtained from our data set was applied to the skeletal Sr/Ca ratios of the modern and fossil corals reported by *Mishima et al.* [2009]. The calibration equations reported so far are highly variable, even among the equations derived from the same genera [*Ayling et al.*, 2006; *Corrège*, 2006]. Thus, the applicability of the existing Sr/Ca-SST relationship should be tested with modern data in the location of interest to take account of the possible offset between individual colonies. Applied to Sr/Ca from the living *D. (F.) speciosa* specimen of *Mishima et al.* [2009], our regression yields SSTs between 22.0°C and 29.4°C, which are in good agreement with the instrumental SST record (21°C–29°C) from Miyako Island. As this agreement validates the applicability of our equation, even around the subtropical Chichi Island, the SST at 16 ka was reconstructed using their fossil *Dipsastraea* (*Favia*) specimen data. Our equation yields Sr/Ca-derived SSTs from 15.7°C to 26.0°C (average = 21.3°C) for the fossil coral at 16 ka, which is approximately 4°C lower than the mean annual SST of the present-day. Considering the ±1.1°C uncertainty associated with our equation, this result agrees with their estimation of a drop of around 5°C at 16 ka, as calculated from the average of the reported slope values. Thus, we propose that our Sr/Ca thermometry has a potential to be widely applicable across subtropical to temperate regions.

5. Conclusions

[29] In mid-latitude regions, the density bands and Sr/Ca ratios preserved in the skeletons of *D. (F.) speciosa* exhibit a clear seasonality that reflects variations in SST. The Sr/Ca-SST relationship, Sr/Ca (mmol/mol) $= 10.184 - 0.0408 \times$ SST (°C), derived from annual extremes of Sr/Ca value and SST, predicted the observed extreme SSTs within an uncertainty of ± 1.1°C for most of the analyzed intervals. This confirms its applicability as a paleo-SST proxy in the northwestern Pacific marginal seas.

[30] However, two slow-growing intervals showed winter peaks that were inconsistent with the observed SSTs. We attribute such low-amplitude winter peaks to the mixing of skeletal parts that grew over slightly different time periods. The diameter of a polyp ($\sim$10 mm) exceeds the average growth rate (6.6 mm/yr on average) in the study area, whose calcification surface is often uneven and not perpendicular to the major growth axis. This characteristic may have resulted in the mixing of asynchronous theca walls when bulk sampling was carried out across the multiple growth lines. This mixing effect seems to be more pronounced during the winter season when the growth rate was lower; however, the SST and the Sr/Ca over the same winter interval showed excellent correspondence in the results from individual spot analyses by LA-ICP-MS. Although SST records can be derived even using the bulk sampling method when the skeletal extension rate is sufficiently high, sampling along a narrow area or individual spot analysis is recommended to obtain the best result. Despite the unfavorable temperature conditions in the study area, frequent growth cessation during the winter was not indicated by the skeletal geochemistry, which confirms its utility as a paleo-SST proxy. As *D. (F.) speciosa* is widely distributed from the tropics to mid-latitudes across the northwestern Pacific [*Veron*, 2000], we suggest that regional oceanographic records could be retrieved from middle-latitude reef cores, allowing an age-based high-resolution comparison of SSTs with their tropical equivalents.

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References

Alibert, C., and L. Kinsley (2008), A 170-year Sr/Ca and Ba/Ca coral record from the western Pacific warm pool: 1. What can we learn from an unusual coral record?, *J. Geophys. Res.*, *113*, C04008, doi:10.1029/2006JC003979.

Allison, N., A. A. Finch, A. W. Tudhope, M. Newville, S. R. Sutton, and R. M. Ellam (2005), Reconstruction of deglacial sea surface temperatures in the tropical Pacific from selective analysis of a fossil coral, *Geophys. Res. Lett.*, *32*, L17609, doi:10.1029/2005GL023183.

Ayling, B. F., M. T. McCulloch, M. K. Gagan, C. H. Stirling, M. B. Anderson, and S. G. Blake (2006), Sr/Ca and δ^{18}O seasonality in a *Porites* coral from the MIS 9 (339–303 ka) interglacial, *Earth Planet. Sci. Lett.*, *248*, 462–475, doi:10.1016/j.epsl.2006.06.009.

Barnes, D. J., R. B. Taylor, and J. M. Lough (1995), On the inclusion of trace materials into massive coral skeletons. Part II: Distortions in skeletal records of annual climate cycles due to growth processes, *J. Exp. Mar. Biol. Ecol.*, *194*, 251–275, doi:10.1016/0022-0981(95)00091-7.

Berkelmanns, R., and M. J. H. van Oppen (2006), The role of zooxanthellae in the thermal tolerance of corals: A "nugget of hope" for coral reefs in an era of climate change, *Proc. R. Soc. B.*, *273*, 2305–2312, doi:10.1098/rspb.2011.0997.

Budd, A. F., H. Fukami, N. D. Smith, and N. Knowlton (2012) Taxonomic classification of the reef coral family Mussidae (Cnidaria: Anthozoa: Scleractinia), *Zool. J. Linnean Soc.*, *166*, 465–529, doi:10.1111/j.1096–3642.2012.00855.x.

Burns, T. P. (1985), Hard coral distribution and cold-water disturbances in South Florida: Variation with depth and location, *Coral Reefs*, *4*, 117–124, doi:10.1007/BF00300870.

Cardinal, D., B. Hamelin, E. Bard, and J. Pätzold (2001), Sr/Ca, U/Ca and δ^{18}O records in recent massive corals from Bermuda: Relationships with sea surface temperature, *Chem. Geol.*, *176*, 213–233, doi:10.1016/S0009-2541(00)00396-X.

Coles, S. L., and Y. H. Fadlallah (1991), Reef coral survival and mortality at low temperatures in the Arabian Gulf: New species-specific lower temperature limits, *Coral Reefs*, *9*, 231–237, doi:10.1007/BF00290427.

Coles, S. L., P. L. Jokiel, and C. R. Lewis (1976), Thermal tolerance in tropical versus subtropical Pacific reef corals, *Pac. Sci.*, *30*, 159–166.

Corrège, T. (2006), Sea surface temperature and salinity reconstruction from coral geochemical tracers, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *232*, 408–428, doi:10.1016/j.palaeo.2005.10.014.

DeLong, K. L., T. M. Quinn, F. W. Taylor, K. Lin, and C.-C. Shen (2013), Improving coral-base paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *373*, 6–24, doi:10.1016/j.palaeo.2012.08.019.

Fallon, S. J., M. T. McCulloch, R. van Woesik, and D. J. Sinclair (1999), Corals at their latitudinal limits: Laser ablation trace element systematics in *Porites* from Shirigai Bay,

Japan, *Earth Planet. Sci. Lett.*, *172*, 221–238, doi:10.1016/S0012-821X(99)00200-9.

Gagan, M. K., L. K. Ayliffe, D. Hopley, J. A. Cali, G. E. Mortimer, J. Chappell, M. T. McCulloch, and M. J. Head (1998), Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific, *Science*, *279*, 1014–1018, doi:10.1126/science.279.5353.1014.

Giry, C., T. Felis, M. Kölling, and S. Scheffers (2010), Geochemistry and skeletal structure of *Diploria strigosa*, implications for coral-based climate reconstruction, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *298*, 378–387, doi:10.1016/j.palaeo.2010.10.022.

Goodkin, N. F., K. Hughen, A. C. Cohen, and S. R. Smith (2005), Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca, *Paleoceanography*, *20*, PA4016, doi:10.1029/2005PA001140.

Goodkin, N. F., K. A. Hughen, S. C. Doney, and W. B. Curry (2008), Increased multidecadal variability of the North Atlantic Oscillation since 1781, *Nat. Geosci.*, *1*, 844–848, doi:10.1038/ngeo352.

Hetzinger, S., M. Pfeiffer, W.-C. Dullo, E. Ruprecht, and D. Garbe-Schönberg (2006), Sr/Ca and δ18O in a fast-growing Diploria strigosa coral: Evaluation of a new climate archive for the tropical Atlantic, *Geochem. Geophys. Geosyst.*, *7*, Q10002, doi:10.1029/2006GC001347.

Hudson, J. H., E. A. Shinn, R. B. Halley, and B. Lidz (1976), Sclerochronology: A tool for interpreting past environments, *Geology*, *4*, 361–364, doi:10.1130/0091-7613(1976)4<361:SATFIP>2.0.CO;2.

Hyeong, K., M. Shimamura, T. Watanabe, H. Yamano, K. Sugihara, and J. Kim (2008), Evaluation of Jeju/Tsushima hermatypic corals as sea surface temperature (SST) recorders [in Korean with English abstract], *Ocean Polar Res.*, *30*, 351–359.

Jacques, T. G., M. E. Q. Pilson, C. Cummings, and N. Marshall (1977), Laboratory observations on respiration, photosynthesis, and factors affecting calcification in the temperate coral *Astrangia danae*, in Proceedings of Third International Coral Reef Symposium Vol. 2: Geology, edited by D. L. Taylor, pp. 455–461, Rosenstiel School of Marine and Atmospheric Science, Miami, FL.

Kemp, D. W., C. A. Oakley, D. J. Thornhill, L. A. Newcomb, G. W. Schmidt, and W. K. Fitt (2011), Catastrophic mortality on inshore coral reefs of the Florida Keys due to severe low-temperature stress, *Global Change Biol.*, *17*, 3468–3477, doi:10.1111/j.1365-2486.2011.02487.x.

Kleypas, J. A., J. W. McManus, and L. A. B. Meñez (1999), Environmental limits to coral reef development: Where do we draw the line?, *Am. Zool.*, *39*, 146–159, doi:10.1093/icb/39.1.146.

LaJeunesse, et al. (2010), Host-symbiont recombination vs. natural selection in the response of coral-dinoflagellate symbioses to environmental disturbance, *Proc. R. Soc. B.*, *277*, 2925–2934, doi:10.1098/rspb.2010.0385.

Leder, J. J., P. K. Swart, A. M. Szmant, and R. E. Dodge (1996), The origin of variations in the isotopic record of scleractinian corals: I. Oxygen, *Geochim. Cosmochim. Acta*, *60*, 2857–2870, doi:10.1016/0016-7037(96)00118-4.

Lough, J. M., and D. J. Barnes (2000), Environmental controls on growth of the massive coral *Porites*, *J. Exp. Mar. Biol. Ecol.*, *245*, 225–243, doi:10.1016/S0022–0981(99)00168-9.

Marshall, J. F., and M. T. McCulloch (2002), An assessment of the Sr/Ca ratio on shallow water hermatypic corals as a proxy for sea surface temperature, *Geochim. Cosmochim. Acta*, *66*, 3263–3280, doi:10.1016/S0016-7037(02)00926-2.

McConnaughey, T. (1989), 13C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns, *Geochim. Cosmochim. Acta*, *53*, 151–162, doi:10.1016/0016-7037(89)90282-2.

McCulloch, M. T., M. K. Gagan, G. E. Mortimer, A. R. Chivas, and P. J. Isdale (1994), A high-resolution Sr/Ca and δ^{18}O coral record from the Great Barrier Reef, Australia, and the 1982–1983 El Niño, *Geochim. Cosmochim. Acta*, *58*, 2747–2754, doi:10.1016/0016-7037(94)90142-2.

Minobe, S., A. Sako, and M. Nakamura (2004), Interannual to interdecadal variability in the Japan Sea based on a new gridded upper water temperature dataset, *J. Phys. Oceanogr.*, *34*, 2382–2397, doi:10.1175/JPO2627.1.

Mishima, M., H. Kawahata, A. Suzuki, M. Inoue, T. Okai, and A. Omura (2009), Reconstruction of the East China Sea palaeoenvironment at 16 ka by comparison of fossil and modern Faviidae corals from the Ryukyus, southwestern Japan, *J. Quat. Sci.*, *24*, 928–936, doi:10.1002/jqs.1268.

Montagna, P., M. McCulloch, C. Mazzoli, S. Silenzi, and R. Odoricoe (2007), The non-tropical coral *Cladocora caespitosa* as the new climate archive for the Mediterranean: High-resolution (∼weekly) trace element systematic, *Quat. Sci. Rev.*, *26*, 441–462, doi:10.1016/j.quascirev.2006.09.008.

Nakata, S., K. Sugihara, T. Irino, T. Watanabe, and H. Yamano (2013), Skeletal growth of Dipsastraea speciosa (Dana, 1846) from the subtropical and temperate regions in Japan, *J. Japan. Coral Reef Society*, in press (in Japanese with English abstract).

Nozaki, Y., D. M. Rye, K. K. Turekian, and R.E. Dodge (1978), A 200 year record of carbon-13 and carbon-14 variations in a Bermuda coral, *Geophys. Res. Lett.*, *5*, 825–828, doi:10.1029/GL005i010p00825.

Okai, T., A. Suzuki, H. Kawahata, S. Terashima, and N. Imai (2002), Preparation of a new geological survey of Japan geochemical reference material: Coral JCp-1, *Geostand. Newsl.*, *26*, 95–99, doi:10.1111/j.1751-908X.2002.tb00627.x.

Omata, T., A. Suzuki, H. Kawahata, S. Nojima, K. Minoshima, and A. Hata (2006), Oxygen and carbon stable isotope systematics in *Porites* coral near its latitudinal limit: The coral response to low-thermal temperature stress, *Global Planet. Change*, *53*, 137–146, doi:10.1016/j.gloplacha.2006.01.009.

Paillard, D., L. Labeyrie, and P. Yiou (1996), Macintosh program performs time-series analysis, *Eos Trans. AGU*, *77*(39), 379, doi:10.1029/96eo00259.

Pätzold, J. (1992), Bermuda coral reef record of the last 1,000 years, paper presented at Fourth international conference on paleoceanography: ICP IV: short-and long-term global change: record modelling: 21-25, September 1992.

Pearce, N. J. G., W. T. Perkins, J. A. Westgate, M. P. Gorton, S. E. Jackson, C. R. Neal, and S. P. Chenery (1997), A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials, *Geostand. Newsl.*, *21*, 115–144, doi:10.1111/j.1751-908X.1997.tb00538.x.

Quinn, T. M. (1993), A 173 year stable isotope record from a tropical south pacific coral, *Quat. Sci. Rev.*, *12*, 407–418, doi:10.1016/S0277-3791(05)80005-8.

Rowan, R. (2004), Coral bleaching: Thermal adaptation in reef coral symbionts, *Nature*, *430*, 742, doi:10.1038/430742a.

Saxby, T., W. C. Dennison, and O. Hoegh-Guldberg (2003), Photosynthetic response of the coral *Montipora digitata* to cold temperature stress, *Mar. Ecol. Prog. Ser.*, *248*, 85–97, doi:10.3354/meps248085.

Schrag, D. P. (1999), Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates, *Paleoceanography*, *14*, 97–102, doi:10.1029/1998PA900025.

Shimamura, M., T. Oba, G. Xu, B. Lu, L. Wang, M. Murayama, K. Toyoda, and A. Winter (2005), Fidelity of $\delta^{18}O$ as a proxy for sea surface temperature: Influence of variable coral growth rates on the coral *Porites lutea* from Hainan Island, China, *Geochem. Geophys. Geosyst.*, *6*, Q09017, doi:10.1029/2005GC000966.

Smith, J. M., T. M. Quinn, K. P. Helmle, and R. B. Halley (2006), Reproducibility of geochemical and climatic signals in the Atlantic coral *Montastraea faveolata*, *Paleoceanography*, *21*, PA1010, doi:10.1029/2005PA001187.

Sugihara, K., and H. Yamano (2004), Tsushima Archipelago, in *Coral Reefs of Japan*, edited by Ministry of the Environment and Japanese Coral Reef Society, pp. 245–247, Minist. of the Environ., Tokyo.

Suzuki, A., M. K. Gagan, K. Fabricius, P. J. Isdale, I. Yukino, and H. Kawahata (2003) Skeletal isotope microprofiles of growth perturbations in *Porites* corals during the 1997–1998 mass bleaching event, *Coral Reefs*, *22*, 357–369, doi:10.1007/s00338-003-0323-4.

Swart, P. K., H. Elderfield, and M. J. Greaves (2002), A high-resolution calibration of Sr/Ca thermometry using the Caribbean coral *Montastraea annularis*, *Geochem. Geophys. Geosyst.*, *3*(11), 8402, doi:10.1029/2002GC000306.

Veron, J. E. N. (2000), Family Faviidae, in *Corals of the World, vol. 3*, edited by M. Stafford-Smith, pp. 85–269, Aust. Inst. of Mar. Sci., Townsville, Queensland.

Walker, N. D., H. H. Roberts, L. J. Rouse, and O. K. Huh (1982), Thermal history of reef-associated environments during a record cold-air outbreak event, *Coral Reefs*, *1*, 83–87, doi:10.1007/BF00301689.

Watanabe, T., and T. Oba (1999), Daily reconstruction of water temperature from oxygen isotopic ratios of a modern *Tridacna* shell using freezing microtome sampling technique, *J. Geophys. Res.*, *104*, 20,667–20,674, doi:10.1029/1999JC900097.

Watanabe, T., M. Minagawa, T. Oba, and A. Winter (2001), Pretreatment of coral aragonite for Mg and Sr analysis: Implications for coral thermometers, *Geochem. J.*, *35*, 265–269.

Watanabe, T., A. Winter, T. Oba, R. Anzai, and H. Ishioroshi (2002), Evaluation of the fidelity of isotope records as an environmental proxy in the coral *Montastraea*, *Coral Reefs*, *21*, 169–178, doi:10.1007/s00338-002-0218-9.

Watanabe, T., M. K. Gagan, T. Corrége, H. Scott-Gagan, J. Cowley, and W. S. Hantoro (2003), Oxygen isotope systematics in *Diploastrea heliopora*: New coral archive of tropical paleoclimate, *Geochim. Cosmochim. Acta*, *67*, 1349–1358, doi:10.1016/S0016–7037(02)01221-8.

Watanabe, T., et al. (2011), Permanent El Niño during the Pliocene warm period not supported by coral evidence, *Nature*, *471*, 209–211, doi:10.1038/nature09777.

Weber, J. N., and P. M. J. Woodhead (1972), Temperature dependence of oxygen-18 concentration in reef coral carbonates, *J. Geophys. Res.*, *77*, 463–473, doi:10.1029/JC077i003p00463.

Yamano, H., K. Hori, M. Yamaguchi, O. Yamagawa, and A. Ohmura (2001), Highest-latitude coral reef at Iki Island, Japan, *Coral Reefs*, *20*, 9–12, doi:10.1007/s003380100137.

Yamano, H., K. Sugihara, T. Nakai, and O. Yamagawa (2004), Iki Islands, in *Coral Reefs of Japan*, edited by Ministry of the Environment and Japanese Coral Reef Society, pp. 242–244, Minist. of the Environ., Tokyo.

Yamano, H., K. Sugihara, and K. Nomura (2011), Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures, *Geophys. Res. Lett.*, *38*, L04601, doi:10.1029/2010GL046474.

Yamano, H., K. Sugihara, T. Watanabe, M. Shimamura, and K. Hyeong (2012), Coral reefs at 34?N, Japan: Exploring the end of environmental gradients, *Geology*, *40*, 835–838, doi:10.1130/G33293.1.