Manuscript submitting to "Global Climate Change and Response of Carbon Cycle in the Equatorial Pacific and Indian Oceans and adjacent landmasses" in ELSEVIER OCEANOGRAPHY SERIES".

Coral records of the 1990s in the northwest Pacific: El Niño, coral bleaching, and global warming

Atsushi Suzuki^{*,a}, Michael K. Gagan^b, Hironobu Kan^c, Ahser Edward^d,
Fernando P. Siringan^e, Minoru Yoneda^f, Hodaka Kawahata^{a,g}

^a *Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8567, Japan*

^b *Research School of Earth Sciences, Australian National University, Canberra, Australia*

^c *Faculty of Education, Okayama University, Okayama 700-8530, Japan*

^d *College of Micronesia, Pohnpei 96941, Federated States of Micronesia*

^e *National Institute of Geological Science, University of The Philippines, Quezon, The Philippines*

^f *National Institute of Environmental Studies, Tsukuba 305-8506, Japan*

^g *Graduate School of Science, Tohoku University, Sendai 980-8578, Japan*

*Corresponding author. Atsushi Suzuki, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba 305-8567, Japan. Tel. +81-298-61-3769; Fax. +81-298-61-3765, e-mail: a.suzuki@aist.go.jp (A. Suzuki)

Abstract. The 1990s were very likely the warmest recorded decade of the second millennium. That decade was also characterized by one of the strongest El Niño-Southern Oscillation (ENSO) events of the 20th century, which occurred in 1997–1998 and was followed by worldwide mass coral bleaching. By comparing high-resolution oxygen isotope records of coral from the northwestern Pacific with instrumental data, we examined the signal recording ability of *Porites* spp. corals relating to these events of the 1990s. The temporal change in skeletal oxygen isotope ratios from Ishigaki Island in the Ryukyus showed good agreement with instrumental sea-surface temperature (SST) data, suggesting that seasonal and interannual variations in the salinity of that region were relatively small. In the western north equatorial Pacific, decreased SST and relative drought characterized the warm ENSO phase. These conditions were faithfully recorded as distinct positive anomalies in coral oxygen isotope records from Micronesia. Bleached *Porites* spp. coral from Ishigaki Island, as well as corals from Pandora Reef of the Great Barrier Reef, showed a growth gap, indicating a substantial decrease in skeletogenesis during the bleaching period. These evidences demonstrate the large potential of coral records to serve as physical and biological indicators of climatic change in the tropical and subtropical waters of the northwestern Pacific, although the coral records available from that region are still limited. (207 words)

Keywords: Oxygen isotope, sea-surface temperature, salinity, ENSO, Western Pacific Warm Pool, climate change

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported (Church et al., 2001) that the 1990s was very likely the warmest decade of the millennium and that 1998 was the warmest year in the instrumental record (1861–2000). The report dared to conclude that most of the warming observed over the last 50 years can be attributed to human activities. A very wide range of physical and biological indicators was listed in the report, together with key observed changes attributable to anthropogenic climate perturbations, including a global rise in mean surface temperature, increased El Niño frequency, and frequent coral bleaching. In this regard, sea-surface temperature (SST) is an important indicator of climate change because the global mean surface temperature is defined as the area-weighted mean of land- and sea-surface temperatures. All three of these indicators, El Niño frequency, coral bleaching, and SST rise, are detectable by analysis of coral skeletal records.

Corals offer rich archives of past climatic variability in tropical and subtropical regions, where instrumental records are limited (Gagan et al., 2000; Church et al., 2001). The oxygen isotopic composition ($\delta^{18}\text{O}_c$) of the coral skeleton is a function of both SST and the oxygen isotopic composition of seawater ($\delta^{18}\text{O}_w$) (McConnaughey, 1989). In oceanic settings where $\delta^{18}\text{O}_w$ is constant, coral $\delta^{18}\text{O}_c$ records SST variability (e.g., Dunbar et al., 1994; Wellington and Dunbar, 1995). In contrast, where $\delta^{18}\text{O}_w$ variations are large compared with SST changes, coral $\delta^{18}\text{O}_c$ records can be used to reconstruct paleoprecipitation (e.g., Linsley et al., 1994) and sea-surface salinity (SSS) (Le Bec et al., 2000).

The synchronous ocean-atmospheric phenomenon known as El Niño-Southern Oscillation (ENSO) appears to occur as a result of an unstable interaction between ocean and atmosphere and comprises contrasting warm (El

Niño) and cold (so-called La Niña) states. El Niño was originally recognized as an unusual warming of the normally cool surface waters off the western coast of South America. ENSO-related climate variations in the low latitudes of the Pacific can be locally recognized as an oscillation between warm-wet and cool-dry conditions. Because the combination of warm and wet or cool and dry conditions serves to increase the amplitude of $\delta^{18}\text{O}_c$ variations, coral $\delta^{18}\text{O}_c$ records are useful for examining past ENSO frequency and related climate variability (e.g., Wellington and Dunbar, 1995).

Long-term trends in SST in the tropical and subtropical seas have been examined based on temporal variations in skeletal $\delta^{18}\text{O}_c$ retrieved from long-lived *Porites* spp. colonies. Gagan et al. (2000) reviewed the latest developments in the use of coral $\delta^{18}\text{O}_c$ records for reconstructing tropical climate over the past several centuries. They pointed out several important findings based on published long-term coral $\delta^{18}\text{O}_c$ records, including (1) a warming/freshening trend during the 19th and 20th century, (2) a contribution to the shift in $\delta^{18}\text{O}_c$ from freshening of the ocean surface too large to neglect, and (3) abrupt, spatially coherent shifts in $\delta^{18}\text{O}_c$ values, possibly related to enhanced volcanism and other global climate events. Long records of ocean temperatures from corals are expected to be particularly valuable for improving our knowledge of climate history (Jones et al., 2001).

Coral bleaching has been described in the literature since the beginning of the 20th century, including an early observation from the Great Barrier Reef (GBR; Yonge and Nicholls, 1931). Since the late 1970s, however, there have been numerous reports of mass bleaching affecting coral reefs in the Caribbean and elsewhere in the tropics (Glynn, 1984). These recurrent coral-bleaching events may be a response to global warming (Glynn, 1990; 1991). Coral bleaching is commonly linked to unusually high SST, which destroys the

symbiotic relationship between the host corals and zooxanthellae (Jokiel and Coles, 1990). During 1997–1998, in particular, severe coral bleaching was reported from many coral reefs in the tropical and subtropical regions of the world. This global-scale coral-bleaching event coincided with one of the strongest ENSO events and the warmest global temperatures on record (Lough, 2000). Thermal stress and bleaching of corals are reported to have caused reduced calcification and lower linear skeletal growth rates (Jokiel and Coles, 1977; Oliver, 1985; Goreau and Macfarlane, 1990; Leder et al., 1991; Tudhope et al., 1992). Suzuki et al. (2000) also identified a distinct reduction in skeletal growth of a *Porites lutea* coral during the 1997–1998 mass-bleaching event in the Ryukyu Islands. However, the effects of bleaching on stable isotope ratios and proxy climate records extracted from coral skeletons have not been fully examined until very recently (Suzuki et al., 2003).

Our purpose here is to demonstrate that long-lived, massive *Porites* spp. corals can provide accurate climatic information suitable for high-resolution paleoclimate reconstructions. We chose to examine corals in the tropical western Pacific because it is an excellent locality for reconstructing both oceanic and atmospheric anomalies associated with ENSO (Gagan et al., 2004). We present high-resolution skeletal $\delta^{18}\text{O}_\text{c}$ records of *Porites* spp. corals from four sites, Ishigaki Island in southern Japan, Bicol in the Philippines, and Chuuk (Truck) Atoll and Pohnpei Island in Micronesia, together with reference samples from Pandora Reef of the GBR. We tested these coral records for their ability to function as archives of climate signals, especially past ENSO and coral-bleaching events and long-term trends in SST.

Study Sites: Northwestern Pacific

The main area sampled for corals in the present study was the northwestern Pacific, where the numbers of reported coral records are still small compared to other areas in the tropics and subtropics (Fig. 1). The study area covers a

relatively wide range of latitude, from Pohnpei Island (7°N) in the equatorial Pacific to Ishigaki Island (24°N) in the Kuroshio Current region of the northwestern Pacific.

The western equatorial Pacific is one of the hottest and wettest tropical ocean regions on Earth. The area in which SST is higher than 28 °C is referred to as the western Pacific Warm Pool (WPWP; Yan et al., 1992) and more recently as the Indo-Pacific Warm Pool (IPWP) including warm areas in Indian Ocean (Gagan et al., 2004). Climatic variability relating to the ENSO cycle is typically large along the equator. However, four Micronesian islands located near the northern border of the WPWP, Palau, Chuuk, Pohnpei, and Majuro, lie along an east–west transect at about 7°N latitude, providing us a unique setting in which to monitor the migration (E–W zonal displacement) and expansion (in total area and in N–S breadth) of the WPWP, both seasonally and in response to the interannual ENSO cycle. Seasonal variations in SST and sea-surface salinity (SSS) show an east-west trend along this island transect (Fig. 1) (Levitus et al., 1994). Annual mean SST increases, and SSS decreases, westward from Majuro to Palau, because Palau is near the center of the IPWP.

Interannual variations of SST and rainfall in the western equatorial Pacific are strongly influenced by the ENSO phenomenon (Fig. 2). From the Philippines to the Micronesian islands, reduced SSTs and relative drought characterize the warm phase, when the WPWP and the Indonesian low atmospheric pressure system migrate eastward toward the central Pacific. Cooling SSTs are probably caused by the shallowing of the thermocline as a result of the relaxation of the trade winds across the Pacific basin, and lower than average rainfall in the WPWP area is a result of zonal displacement of convective centers of the Walker Circulation.

Two of four coral sites, Bicol (13°N, 124°N), near the southeastern tip of Luzon Island, the Philippines, and Ishigaki Island, one of the Ryukyu Islands in the East China Sea, are located along the route of the warm Kuroshio Current

(Fig. 1). Bicol is close to the point where the North Equatorial Current bifurcates, forming the northward flowing Kuroshio and the southward flowing Mindanao Current. Bicol appears to be located near the center of the area of reduced rainfall during El Niño events, but the local SST there shows little correlation with the Southern Oscillation Index (SOI; Treberth and Hoar, 1996), which is a widely recognized index of ENSO activity (Fig. 2). Seasonal variation becomes larger toward Ishigaki Island from the Bicol region (Fig. 1). In terms of interannual variation of SST at Ishigaki Island, the majority of the highest SST measurements have been obtained during summers following the onset of El Niño events (warm phase of ENSO), indicating a teleconnection linking Ishigaki SST to ENSO (Suzuki et al., 1999; 2003). Park and Oh (2000) reported a teleconnection pattern between the East China Sea and the equatorial Pacific: SSTs in the East China Sea show significant coherence with SSTs in the Niño 3.4 region, with a phase lag of 5–9 months. Therefore, the anomalously warm SSTs around the Ryukyus in 1998, which resulted in severe coral bleaching in the area, may have been related to the 1997–1998 El Niño.

Materials and Methods

Micronesia

Vertical coral cores were retrieved from *Porites* colonies at Chuuk Atoll (8°N, 152°E) and Pohnpei Island (7°N, 158°E) of the Federated States of Micronesia (Fig. 1). A 180-cm-long coral core was extracted on March 11–12, 1999, from a *Porites lutea* colony at 3.9 m depth (below mean sea level; MSL) in a channel of the outer reef near the Northeast Pass, Chuuk Atoll. The core (sample ID: CHU99-01) was sectioned into 7-mm-thick slabs, which were cleaned with deionized water. Coral slabs were processed according to the microsampling procedures described by Gagan et al. (1994; 1998). The microsampling interval was 400 μ m along the major growth axis of the core, and about 50 samples on average per annual growth increment were collected.

Isotope measurements were carried out on every four samples for about 17 cm from the surface of the colony, corresponding to a time resolution of about one month.

A 97-cm-long coral core (sample ID: POH99-02) was recovered from a *Porites* sp. colony at about 1.0 m below MSL on the coral reef about 2 km off the airport near Kolonia, Pohnpei Island, on March 15, 1999 (Inoue et al., 2004). The same procedures were employed for microsampling this core.

Although we obtained *Porites* sp. coral cores in the lagoon of Majuro Atoll in 1999, we here discuss only the result of SST monitoring at the Central Shoal in the lagoon.

Bicol, the Philippines

Coring was conducted on a live *Porites* sp. coral colony off the northern coast of Sawanga, a village in the City of Sorsogon, Bicol (Region V), the Philippines (13°N, 124°E; Fig. 1). The coral collection site was near the wide opening of Albay Gulf into the Philippine Sea (the western Pacific). The colony was growing on a gentle outer reef slope about 6 m below MSL, and the colony height was 2.5 m. The core was extracted from the top of the colony (sample ID: SWGM01-01).

Ishigaki Island, the Ryukyus

Corals were collected from three sites around Ishigaki Island (24°N, 124°E; Fig. 1). A *P. australiensis* coral (sample ID: IU96-07) growing at 3.5 m below MSL in relatively well-flushed conditions, was collected on November 22, 1996, from Urasoko Bay, along the northern coast of the island (Suzuki et al., 1999). Another small coral (*P. lutea*; sample ID: IS91-06; diameter < 20 cm) was collected from the bottom of a moat (2 m below MSL) in the lee of the fringing reef off the southeastern coast (Suzuki et al., 2001).

A *Porites lutea* colony forming a fused complex in a reef channel off Yasura-zaki in the northern part of the island became discolored during the

1998 mass-bleaching event, but other *Porites* colonies showed no change in color (Suzuki et al., 2003). Vertical coral cores were extracted from the tops of nonbleached (sample ID: IY99-01) and bleached (IY99-02) colonies on February 2, 1999, approximately 6 months after the onset of bleaching in this region.

Coral specimens, except for IU96-07, were microsampled along the major growth axis vertically according to the same method as described above. About 50 samples on average per annual growth increment were collected. The microsampling of the specimen IU96-07 along the major growth axis was conducted using a microdrill with a 0.5-mm-diameter bit, as described by Suzuki et al. (1999).

Pandora Reef, GBR

Pandora Reef is the reference coral site of this study. Several short coral cores (6–13 cm long) were collected from three massive *Porites* spp. colonies at 5 m depth on the seaward side of Pandora Reef (18°S, 146°E) on January 14, 1999 (Suzuki et al., 2003). We examined two cores from a collection of drilled specimens. One core (PAN-1-B) was extracted from the side of a large *Porites lutea* colony. Sample PAN-3 was extracted from the side of a *Porites* cf. *lutea/australiensis* colony (~1 m diameter). Coral bleaching was reported initially at Pandora Reef in March 1998, the end of the austral summer, and 1 month after a large flooding event. Thus, the date of sample collection was approximately 9 months after the onset of mass bleaching. All coral cores were taken from the sides of the colonies to minimize damage to the colonies from the coring.

Isotopic measurements

Isotopic analyses of 70–130 µg of microsamples from each coral core CHU99-01, POH99-02, SWGM01-01, IY99-01, IY99-02, PAN99-01-B, and PAN99-03 were conducted by reacting the coral aragonite with 100% H₃PO₄ at

90 °C in an automated individual-carbonate reaction device (Multiprep, Micromass, UK) coupled with a Micromass Optima mass spectrometer at the Geological Survey of Japan, AIST (Suzuki et al., 2000). Carbonate samples for IS91-06 were processed by an automated individual carbonate reaction (Kiel) device attached to a Finnigan-MAT251 mass spectrometer at the Australian National University (Gagan et al., 1994; Suzuki et al., 2001). Isotopic data are reported as per mil (‰) deviations relative to V-PDB (Vienna Peedee Belemnite) (Coplen, 1996). Both mass spectrometers had comparable internal precision for oxygen isotope ratios: $\sim 0.04\text{‰}$ (1σ). In the present study, the oxygen isotope ratios in water are also expressed using the same conventional δ notation as for coral carbonate but the reference material is the Vienna-Standard Mean Ocean Water standard (VSMOW) (Coplen, 1996).

Instrumental records

For comparison with skeletal isotopic data, several time-series of instrumental records of marine parameters are examined. For the SST time-series, IGOSS NMC (Integrated Global Ocean Services System Products Bulletin, National Meteorological Center) blended ship and satellite data for each 1° square since 1982 were used (Reynolds and Smith, 1994). Because some differences between satellite-based and in situ SSTs have been reported in inshore waters (Gagan et al., 1996; Suzuki et al., 1999), we conducted in situ measurements of SST at Chuuk, Pohnpei, Majuro, Bicol, and Ishigaki using TidbiT temperature loggers. In situ SSS measurements in the tropical Pacific for 1969–1995 have been compiled and gridded by Institut de Recherche pour le Développement (IRD) Center in Nouméa (Delcroix, 1998; <http://www.ird.nc/ECOP/>), so a monthly SSS time-series for the grid between $6\text{--}8^\circ\text{N}$ and $145\text{--}155^\circ\text{E}$ was compared with Chuuk coral records.

Results and Discussion

Coral $\delta^{18}\text{O}$ record as a SST proxy at Ishigaki Island.

As the *Porites australiensis* colony (IU96-07) in Urasoko Bay, Ishigaki Island is only 300 m from a long-term daily temperature monitoring station (Yaeyama Station, Japan Sea-Farming Association), the coral specimen from this colony was considered a good material for proxy signal calibration of skeletal $\delta^{18}\text{O}_c$ (Fig. 4). Suzuki et al. (1999) proposed the temperature-skeletal $\delta^{18}\text{O}_c$ relationship shown below:

$$\delta^{18}\text{O}_c (\text{‰}) = -0.611 - 0.165T (^\circ\text{C}) \quad (1)$$

Annual variation of SST around Ishigaki Island is about 10 °C, and the seasonal salinity change is less than 0.5. Therefore, the effects of seasonal variation of salinity on the $\delta^{18}\text{O}_w$ value of reef water can be neglected in the first approximation. Suzuki et al. (1999) pointed out that equation (1) is relatively close to those reported earlier for *Porites* spp. corals from other regions of the Pacific, but differs from that reported by Mitsuguchi et al. (1996) for *Porites lutea* from a reef channel off Yasura-zaki on the eastern coast of Ishigaki Island (Fig. 6). Suzuki et al. (1999) suggested that the lower frequency of microsampling by Mitsuguchi et al. (1996) is a possible cause of the difference in the slope of the SST– $\delta^{18}\text{O}_c$ relationship between the two studies, because a lower sample frequency would be expected to result in the attenuation of seasonal $\delta^{18}\text{O}_c$ signals.

Through multiple deployments of temperature loggers at the coral sites, we found that IGOSS SSTs generally showed excellent agreement with in situ temperature records in tropical regions, including the Micronesian islands and Bicol (Fig. 3). However, wintertime IGOSS NMC SSTs showed a relatively large difference of up to 2°C with in situ SSTs monitored at moats (shallow lagoons) in the Shiraho and Yasura-zaki areas of Ishigaki Island, suggesting a possible limitation of the use of satellite-based SST for comparison with high-

latitude coral records. On the other hand, SST records from Ishigaki Port collected by the Japan Meteorological Agency (JMA) showed good agreement with in situ SSTs at coral sites around Ishigaki Island. Thus, we examined two coral specimens from the Shiraho and Yasura-zaki coral reefs for $\delta^{18}\text{O}_c$ signal calibration against SST records. SST–skeletal $\delta^{18}\text{O}_c$ relationships obtained for colonies IU91-06 (Shoraho reef) and IY99-01 (Yasura-zaki channel) are shown by equations (2) and (3), respectively:

$$\delta^{18}\text{O}_c (\text{‰}) = -1.444 - 0.140T (\text{°C}) \quad (2)$$

$$\delta^{18}\text{O}_c (\text{‰}) = -0.999 - 0.148T (\text{°C}) \quad (3).$$

These slopes are in between values reported by Mitsuguchi et al. (1996; $-0.134\text{‰}^\circ\text{C}^{-1}$) and Suzuki et al. (1999; $-0.165\text{‰}^\circ\text{C}^{-1}$). Because the microsampling frequency of these two specimens (IU91-06 and IY99-01) was comparable to that of IU96-01 (Suzuki et al., 1999), the smaller slopes obtained for IU91-06 and IY99-01 cannot be attributed to signal attenuation caused by a lower frequency of microsampling. This relatively large variation in the SST– $\delta^{18}\text{O}_c$ relationship found in a single island may be related to biological and genetic factors rather than to a difference in microenvironments. Further research, including examination of interspecies differences in the genus *Porites*, is needed to determine the cause of the variation. Keeping these caveats relating to the SST– $\delta^{18}\text{O}_c$ calibration in mind, we believe that the similarity between the skeletal $\delta^{18}\text{O}_c$ profiles and the in situ SST time-series (Fig. 5) suggests that coral $\delta^{18}\text{O}_c$ records can be used as a good proxy for SST with negligible influence from SSS variation.

ENSO signals in the coral $\delta^{18}\text{O}$ record from Micronesia

As expected from seasonal variations in SST and SSS (Fig. 1), annual periodicity was clearly observed in $\delta^{18}\text{O}_c$ profiles of the Chuuk and Pohnpei corals (Fig. 4). We employed a coral chronology based on peak matching between skeletal $\delta^{18}\text{O}_c$ and instrumental SST with simple interpolation; the minima and maxima in annual $\delta^{18}\text{O}_c$ curves were designated as the highest and lowest annual SSTs (Fig. 7). Comparison of the monthly $\delta^{18}\text{O}_c$ profile of Chuuk coral CHU99-01 with times-series of environmental variables (A.D. 1980 to 1999) revealed a modal change in annual $\delta^{18}\text{O}_c$ variation relating to the ENSO cycle (Fig. 7). During non-El Niño periods, a combination of warm SSTs and high rainfall in the wet season (June–November) causes coral $\delta^{18}\text{O}_c$ values to decrease, whereas the cooler dry season (December–May) produces high $\delta^{18}\text{O}_c$ values. On the other hand, pronounced $\delta^{18}\text{O}_c$ shifts toward the positive are recognized during ENSO warm-phase maxima, corresponding to the SST decrease and drought conditions around Chuuk Atoll. Similar climate variations are recorded in skeletal compositions of corals living near the WPWP, including off the north coast of Papua New Guinea (Tudhope et al., 1995; 2001) and off North Sulawesi, Indonesia (Moore et al., 1997; Hughen et al., 1999), and Fiji (Le Bec et al., 2000). In detail, the amplitude of the $\delta^{18}\text{O}_c$ anomaly corresponds well to El Niño intensity as indicated by SOI values; the unusually strong El Niño event of 1982–1983, which had widespread ecological and economic impact, shows the largest anomaly in the $\delta^{18}\text{O}_c$ profile (Fig. 7).

Coral $\delta^{18}\text{O}_c$ values of CHU99-01 showed moderate correlation with both SST and SSS, reflecting that SST and SSS in the region fluctuate with comparable amplitude with respect to the coral $\delta^{18}\text{O}_c$ signal (Fig. 8). Although

when all $\delta^{18}\text{O}_c$ data were plotted against SST, the slope of the regression line was different from that of the temperature dependency relationship for coral aragonite (0.13‰ – 0.18‰ $^{\circ}\text{C}^{-1}$; Fig. 8), the discrepancy can be attributed to changes of $\delta^{18}\text{O}_w$ in seawater during the ENSO cycle. Coral $\delta^{18}\text{O}_c$ values corresponding to the warm phase of ENSO showed an evident shift toward the heavier end of the $\delta^{18}\text{O}$ axis owing to ^{18}O enrichment in the seawater.

The intra-annual $\delta^{18}\text{O}_c$ fluctuations were well recovered by high-resolution microsampling, so the temporal evolution of each El Niño event can be discussed using coral records. El Niño events are usually characterized by initial cooling of SSTs in the tropical western Pacific, followed by lower than average rainfall. A distinct positive shift in $\delta^{18}\text{O}_c$ in the year of a strong El Niño can be attributed to this initial cooling. The skeletal $\delta^{18}\text{O}_c$ values for the year following a strong El Niño peak does not vary much, suggesting the persistence of cool and/or high-salinity conditions for almost a year (Fig. 7). Although the lower SST can be attributed primarily to the eastward migration of the WPWP during the El Niño event, the shallowing of the thermocline brought about by relaxation of the trade winds across the Pacific basin is also important for surface cooling. High-salinity conditions in the year following a strong El Niño also appear to be caused by the shallowing of the thermocline, along with the effect of the decrease in rainfall locally. Because rainfall and SST data quickly recovered to normal levels just after the El Niño peak, salt advection by the North Equatorial Counter Current and/or subsurface mixing due to transformation of a “barrier layer” (Lukas and Lindstrom, 1991) seems to account for the relatively positive $\delta^{18}\text{O}_c$ anomalies in the years following the El Niño peak.

The combination of a $\delta^{18}\text{O}_\text{c}$ shift toward the positive followed by a compressed curve can be used as a signal of an El Niño event in this region, because these features were also seen in Pohnpei Island coral (Fig. 4). The coral $\delta^{18}\text{O}_\text{c}$ record also shows a potential for quantitative examination of the individual characteristics and temporal evolution of each past El Niño event. Such an examination would improve our understanding of the ENSO cycle, although additional measurements of the skeletal Sr/Ca ratio, an independent proxy for SST, are desirable for more a precise reconstruction. Further $\delta^{18}\text{O}_\text{c}$ measurements on longer cores would allow us to explore changes in the frequency of the ENSO cycle over the past several centuries and the effect of global warming on this important cycle.

Skeletal records of coral bleaching

Extensive coral bleaching was witnessed in the GBR, Australia, during the austral summer of 1997–1998 and appeared later in the Northern Hemisphere (Wilkinson, 1998). For the first time on record, corals around the Ryukyu Islands, Japan, exhibited severe bleaching, which resulted in extensive coral mortality (Fujioka, 1999). The most likely cause of the high-SST event around the Ryukyus in the summer of 1998 was the lack of typhoons in the Ryukyu Islands region (Fujioka, 1999). Low-pressure systems, including tropical typhoons, bring high cloudiness and stimulate vertical mixing of the surface water, which may result in an SST decrease. In the absence of typhoons during the summer of 1998, SST continued to rise because of solar heating during the summer of 1998 and resulted in the extraordinarily high SST around Ishigaki Island (daily mean SST of 31.5 °C; Fig. 3), which caused the mass-bleaching event.

While there has been remarkable progress in understanding the photophysiological processes of coral bleaching (Lesser, 1996; Brown, 1997),

less is known about the effect of bleaching on coral skeletogenesis. Moreover, the influence of bleaching on the geochemical composition ($\delta^{18}\text{O}_\text{c}$, $\delta^{13}\text{C}$, and Sr/Ca ratio) of coral skeletons has been controversial. Some studies reported clear changes associated with bleaching events, while these changes remained less evident in other reports (Porter et al., 1989; Leder et al., 1991; Alison et al., 1996). Since bleaching can result in a substantial decrease in skeletogenesis, a very fine sampling technique is needed to detect the corresponding isotopic changes in the coral skeleton. Recently, Suzuki et al. (2003) introduced a high-resolution skeletal isotope microprofiling technique for examining the skeletal records of coral bleaching (Fig. 9). When this technique was used, bleached corals from Pandora Reef, GBR, and Ishigaki Island, Japan, showed a dramatic decrease in skeletogenesis that was coincident with the worldwide severe bleaching event of 1997–1998. The results indicate that isotopic microprofiling may be the key to identifying gaps in coral growth that are diagnostic of past bleaching events.

Decreasing trend in coral $\delta^{18}\text{O}$: an indication of global warming?

Figure 10 shows coral $\delta^{18}\text{O}_\text{c}$ time-series for the last two decades of the 20th century for four coral sites. To construct an age model of each coral record, peak matching between $\delta^{18}\text{O}_\text{c}$ and instrumental SST with simple interpolation was employed. In the Bicol coral record, a decreasing trend in $\delta^{18}\text{O}_\text{c}$ ($-0.05\text{‰}/10\text{ yr}$) was found even in over the relatively short period between 1980 and 2000, which may suggest an SST rise and/or surface-water freshening related to global warming. A decreasing trend in $\delta^{18}\text{O}_\text{c}$ in the Micronesian corals may have been masked by the large number of ENSO events, which caused local cooling (hence, a $\delta^{18}\text{O}_\text{c}$ increase), during the latter part of the period. Warming/freshening trends have been found generally in

coral $\delta^{18}\text{O}_c$ records from several sites in the tropical Pacific and Indian oceans (Gagan et al., 2000).

In Fig. 10, coral $\delta^{18}\text{O}_c$ curves are also matched to instrumental SSTs based on the $\delta^{18}\text{O}_c$ –SST relation obtained for each coral site. We have shown that coral records from the Micronesian islands, and possibly the Philippines, are influenced by seawater $\delta^{18}\text{O}_w$ variation. Therefore, the coral-based SSTs from these sites should be referred as “apparent” SSTs (Gagan et al., 2000) because the influences of seawater $\delta^{18}\text{O}_w$ variation are not taken into account in the estimation procedure. It is also assumed that all changes in $\delta^{18}\text{O}_c$ can be attributed to temperature variation, but salinity changes also influence $\delta^{18}\text{O}_c$ values. When we look at overall trends in instrumental and coral-derived “apparent” SSTs, these show a good agreement at each coral site, suggesting that coral records have potential as an SST proxy when discussing long-term trends. High-latitude sites showed a more rapidly increasing trend in SST values during the last two decades of the 20th century. Although the long-term instrumental SST data available since 1914 for Ishigaki Port showed a distinct warming trend of 0.12 °C/10 yr throughout the monitoring period (Suzuki et al., 2003), the observed SST increase during the last two decades (0.57 °C/10 yr) is large compared with the earlier part of the century.

Comparison of “apparent” and instrumental SSTs is also a useful tool for identifying El Niño-related severe drought events in the western Pacific. “Apparent” SSTs during the year 1998 for Bicol and the Micronesian sites were low relative to actual SSTs (Fig. 10). As discussed in relation to $\delta^{18}\text{O}_c$ curves for the year 1998 from Chuuk Atoll, the deviation of the $\delta^{18}\text{O}_c$ curve from the instrumental SST curve can be attributed to increased seawater $\delta^{18}\text{O}_w$ (higher salinity), corresponding to local drought (Fig. 7). The Philippines

experience more severe drought conditions compared with the Micronesian islands, as seen in the pattern of annual precipitation anomalies associated with strong El Niño events (Fig. 2B), and, indeed, coral records from Bicol showed the largest deviation among the three sites examined.

Summary

High-resolution $\delta^{18}\text{O}_\text{c}$ records from annually banded modern *Porites* spp. corals collected in the western Pacific have been used successfully to monitor recent marine climatic events, including the strong El Niño in 1997–1998, severe coral bleaching, and long-term SST rise. In the relatively high-latitude region of the western Pacific (the Ryukyu Islands of Japan), coral $\delta^{18}\text{O}_\text{c}$ records are a good proxy for SST because of the limited influence from rainfall. In contrast, temporal variation in coral $\delta^{18}\text{O}_\text{c}$ from the Micronesian islands appeared to be affected by both SST and SSS variations. The temporal $\delta^{18}\text{O}_\text{c}$ pattern of a distinct positive shift followed by a compressed curve found in Micronesian corals can be a useful signal for identifying past El Niño events in long coral records from the region. Using the bleached corals collected from Ishigaki Island as well as from Pandora Reef of the GBR, the isotope microprofiling technique allowed us to find a growth gap, which was caused by the warmer than normal SST related to the 1997–1998 El Niño; such a gap can be used as an important skeletal indicator for reconstructing past bleaching events. On the Pacific side of the Philippine Islands, a decreasing trend in $\delta^{18}\text{O}_\text{c}$ was found even over the relatively short period between 1980 and 2000, which may suggest an SST rise and/or surface-water freshening related to global warming. In the Micronesian corals, a global warming trend may have been masked by the influence of the large number of ENSO events, which causes local cooling, toward the end of the record.

The above discussion is not based on results of a comprehensive analyses of coral records from the northwestern Pacific. However, the results are intriguing enough to warrant further data acquisition and attempts at quantitative time-series analysis. Our results also demonstrated that high-resolution coral $\delta^{18}\text{O}_\text{c}$ records have potential for future studies of the climate during not only the recent past but also the distant past, including the mid-Holocene and the later interglacial periods, which may be important analogs of the future greenhouse Earth.

Acknowledgments. We express our appreciation to H. Adachi of Geoact Co., Ltd. for coral coring. Coral specimens from Pandora Reef were provided by Katrina Fabricius of the Australian Institute of Marine Science. We are also grateful to K. Minoshima, who performed isotopic analyses on coral samples. Assistance in the field was given by S. Akama and M. Yoshino, and assistance in the laboratory by Y. Yoshinaga, I. Yukino, S. Oyamada, H. Muramatsu, and Y. Sato. Coral specimens were identified by R. van Woesik of the University of the Ryukyus. This study was funded by both the Ministry of Education, Sports, Science and Technology (MEXT) of Japan through the Special Coordination Fund “GCMAPS” program and the Ministry of the Environment of Japan for a “Study on the increase of sea-surface temperature in the Asian Monsoon region based on coral skeletal climatology,” with additional support from the National Institute of Advanced Industrial Science and Technology (AIST).

References

Alison, N., Tudhope, A.W., Fallick, A.E., 1996. Factors influencing the stable carbon and oxygen isotope composition of *Porites lutea* coral skeletons from Phuket, South Thailand. *Coral Reefs* 14, 43–57.

- Brown, B.E., 1997. Coral bleaching: cause and consequences. *Coral Reef* 16, S129–138.
- Church, J.A. et al., 2001. *Climate Change 2001: The Scientific Basis* (ed. Houghton, J. T.) Cambridge Univ. Press, New York.
- Coplen, T.B., 1996. New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data, *Geochimica et Cosmochimica Acta* 60, 3359–3360.
- Dai, A., Wigley, T.M.L., 2000. Global patterns of ENSO-induced precipitation. *Geophysical Research Letters* 27, 1283–1286.
- da Silva, A., Young, A.C., Levitus, S., 1994. *Atlas of Surface Marine Data 1994, Volume 1: Algorithms and Procedures*. NOAA Atlas NESDIS 6, U.S. Department of Commerce, Washington, D.C.
- Delcroix, T., 1998. Observed surface oceanic and atmospheric variability in the tropical Pacific at seasonal and ENSO timescales: A tentative overview. *Journal of Geophysical Research* 103, 18611–18633.
- Dunbar, R.B., Wellington, G.M., Colgan, N.W., Glynn, P.W., 1994. Eastern Pacific climate variability since 1600 A.D.: stable isotopes in Galapagos corals. *Paleoceanography* 9, 291–315.
- Fujioka, Y., 1999. Mass destruction of the hermatypic corals during a bleaching event in Ishigaki Island, southwestern Japan. *Galaxea, Journal of Japanese Coral Reef Society* 1, 41–50.
- Gagan, M.K., Ayliffe, L.K., Beck, J.W., Cole, J.E., Druffel, E.R.M., Dunbar, R.B., Schrag, D.P., 2000. New views of tropical paleoclimates from corals. *Quaternary Science Reviews* 19, 45–64.
- Gagan, M.K., Ayliffe, L.K., Hopley, D., Cali, J.A., Mortimer, G.E., Chappell, J., McCulloch, M.T., Head, M.J., 1998. Temperature and surface-ocean water balance of the Mid-Holocene tropical western Pacific. *Science* 279, 1014–1018.

- Gagan, M.K., Chivas, A.R., Isdale, P.J., 1994. High-resolution isotopic records from corals using ocean temperature and mass-spawning chronometers, *Earth and Planetary Science Letters* 121, 549–558.
- Gagan, M.K., Chivas, A.R., Isdale, P.J., 1996. Timing coral-based climatic histories using ^{13}C enrichments driven by synchronized spawning. *Geology* 24, 1009–1012.
- Gagan, M.K., Hendy, E.J., Haberle, S.G., Hantoro, W.S., 2004. Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño-Southern Oscillation. *Quaternary International* 118–119, 127–143.
- Glynn, P.W., 1984. Widespread coral mortality and the 1982/83 El Niño warming event. *Environmental Conservation* 11, 133–146.
- Glynn, P.W., 1990. Coral mortality and disturbances to coral reefs in the tropical eastern Pacific. In: Glynn P.W. (ed) *Global Consequences of the 1982-83 El Niño-Southern Oscillation*. Elsevier, Amsterdam, pp. 55–67.
- Glynn, P.W., 1991. Coral reef bleaching in the 1980s and possible connections with global warming. *Trends in Ecology and Evolution* 6, 175–179.
- Goreau, T., Macfarlane, A.H., 1990. Reduced growth rate of *Montastrea annularis* following the 1987–1988 coral-bleaching event. *Coral Reefs* 8, 211–215.
- Hughen, K.A., Schrag, D.P., Jacobsen, S.B., Hantaro, W., 1999. El Niño during the last interglacial period recorded by a fossil coral from Indonesia, *Geophysical Research Letters* 26, 3129–3132.
- Inoue, M., Suzuki, A., Nohara, M., Kan, H., Edward, A., Kawahata, H., 2004. Coral skeletal tin and copper concentration at Pohnpei, Micronesia: Possible index for marine pollution by toxic anti-biofouling paints. *Environmental Pollution* 129, 399–407.
- Jokiel, P.L., Coles, S.L., 1977. Effects of temperature on the mortality and growth of Hawaiian reef corals. *Marine Biology* 43, 201–208.

- Jokiel, P.L., Coles, S.L., 1990. Responses of Hawaiian and other Indo-Pacific reef corals to elevated temperatures. *Coral Reefs* 8, 155–162.
- Jones, P.D., Osborn, T.J., Briffa, K.R., 2001. The evolution of climate over the last millennium. *Science* 292, 662–667.
- Le Bec, N., Juillet-Leclerc, T.A., Delcroix, 2000. A coral $\delta^{18}\text{O}$ record of ENSO driven sea surface salinity variability in Fiji (south-western tropical Pacific), *Geophysical Research Letters* 27, 3897–3900.
- Leder, J.J., Szmant, A.M., Swart P.K., 1991. The effect of prolonged “bleaching” on skeletal banding and stable isotopic composition in *Montastrea annularis*. Preliminary observations. *Coral Reefs* 10, 19–27.
- Lesser, M.P., 1996. Elevated temperatures and ultraviolet radiation cause oxidative stress and inhibit photosynthesis in symbiotic dinoflagellates. *Limnology Oceanography* 41, 271–283.
- Levitus, S., Burgett, R., Boyer, T., 1994. World Ocean Atlas Volume 3: Nutrients, NOAA Atlas NESDIS, 3. U.S. Department of Commerce, Washington, D.C.
- Linsley, B.K., Dunbar, R.B., Wellington, G.M., 1994. A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707. *Journal of Geophysical Research* 99, 9977–9994.
- Lough, J.M., 2000. 1997–98: Unprecedented thermal stress to coral reefs? *Geophysical Research Letters* 27, 3901–3904.
- Lukas, R., Lidstrom, E., 1991. The mixed layer of the western equatorial Pacific Ocean, *Journal of Geophysical Research* 96, suppl., 3343–3358.
- McConnaughey, T., 1989. ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns. *Geochimica et Cosmochimica Acta* 53, 151–162.
- Mitsuguchi, T., Matsumoto, E., Abe, O., Uchida, T., Isdale, P.J., 1996. Mg/Ca thermometry in coral skeletons. *Science* 274, 961–963.

- Moore, M.D., Schrag, D.P., Kashgarian, M., 1997. Coral radiocarbon constraints on the source of the Indonesian throughflow. *Journal of Geophysical Research* 102, 12359–12365.
- Oliver, J., 1985. Recurrent seasonal bleaching and mortality of corals on the Great Barrier Reef. *Proceedings of 5th International Coral Reef Symposium* 4, 201–206.
- Palillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis, *EOS Trans. AGU*, 77, 379.
- Park, W.S., Oh, I.S., 2000. Interannual and interdecadal variations of sea surface temperature in the East Asian Marginal Seas. *Progress in Oceanography* 47, 191–204.
- Porter, J.W., Fitt, W.K., Spero, H.J., Rogers, C.S., White, M.W., 1989. Bleaching in reef corals: Physiological and stable isotopic responses. *Proceedings of National Academy of Science USA* 86, 9342–9346.
- Reynolds, R.W., Smith, T.M., 1994. Improved global sea surface temperature analyses using optimal interpolation, *Journal of Climate* 7, 928–948.
- Suzuki, A., Kawahata, H., Tanimoto, Y., Tsukamoto, H., Gupta L.P., Yukino I., 2000. Skeletal isotopic record of a *Porites* coral during the 1998 mass bleaching event. *Geochemical Journal* 34, 321–329.
- Suzuki, A., Gagan, M.K., De Deckker, P., Omura, A., Yukino, I., Kawahata, H., 2001. Last Interglacial coral record of enhanced insolation seasonality and seawater ^{18}O enrichment in the Ryukyu Islands, northwest Pacific. *Geophysical Research Letters* 28, 3685–3688.
- Suzuki, A., Gagan, M.K., Fabricius, K., Isdale, P.J., Yukino, I., Kawahata, H., 2003. Skeletal isotope microprofiles of growth perturbations in *Porites* corals during the 1997–1998 mass bleaching event. *Coral Reefs* 22, 357–369.
- Suzuki, A., Yukino, I., Kawahata, H., 1999. Temperature-skeletal $\delta^{18}\text{O}$ relationship of *Porites australiensis* from Ishigaki Island, the Ryukyu, Japan. *Geochemical Journal* 33, 419–428,

- Trenberth, K.E., Hoar, T.J., 1996. The 1990–1995 El Niño–Southern Oscillation event: Longest on record. *Geophysical Research Letters* 23, 57–60.
- Tudhope, A.W., Allison, N., Le Tissier, M.D.A., Scoffin, T.P., 1992. Growth characteristics and susceptibility to bleaching in massive *Porites* corals, South Thailand. *Proceedings of 7th International Coral Reef Symposium* 1, 64–69.
- Tudhope, A., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R. M., Lea, D.W., Lough, J.M., Shimmield, G.B., 2001. Variability in the El Niño–Southern Oscillation through a glacial–interglacial cycle. *Science* 291, 1512–1517.
- Tudhope, A., Shimmield, G.B., Chilcott, C.P., Jebb, M., Fallick, A.E., Dalgleish, A.N., 1995. Recent changes in climate in the far western equatorial Pacific and their relationship to the Southern Oscillation; oxygen isotope records from massive corals, Papua New Guinea. *Earth and Planetary Science Letters* 136, 575–590.
- Wilkinson, C., 1998. The 1997–1998 mass bleaching event around the world. In: Wilkinson C (ed) *Status of Coral Reefs of the World: 1998*. Australian Institute of Marine Science, Townsville, pp. 15–38.
- Wellington, G.M., Dunbar, R.B., 1995. Stable isotope signature of El Niño–Southern Oscillation events in eastern tropical Pacific reef corals. *Coral Reefs* 14, 5–25.
- Yan, X.-H., Ho, C.-R., Zheng, Q., Klemas, V., 1992. Temperature and size variabilities of the Western Pacific Warm Pool. *Science* 258, 1643–1645.
- Yonge, C.M., Nicholls, A.G., 1931. *Studies on the physiology of corals. IV. The structure, distribution and physiology of the zooxanthellae*. Great Barrier Reef Expedition 1928–29 Science Report 1, 135–176.

Figure captions

Figure 1. (Upper Panel) Location of study sites in the western Pacific. The locations of the Indo-Pacific Warm Pool (IPWP, mean annual SST $>28^{\circ}\text{C}$) is shown, together with the average position of the Intertropical Convergence Zone (ITCZ) in July and January. (Lower Panel) Climatological monthly sea-surface temperature (SST), and sea-surface salinity (SSS) at each coral site. The DASILVA SMD94 climatology data (da Silva et al., 1994; <http://ingrid.ldeo.columbia.edu/SOURCES/.DASILVA/.SMD94/.climatology/>) and data from Levitus et al. (1994) were used for SST and SSS, respectively.

Figure 2. (A) Map of correlations of the smoothed Southern Oscillation Index (SOI; negative Darwin sea-level pressure anomalies) with monthly SST anomalies for 1950 to 1994 (contour interval, 0.1). Magnitudes of regression coefficient (R) exceeding $+0.7$ and -0.7 are lightly and darkly shaded, respectively. The map is reproduced from Trenberth and Hoar (1996). (B) Pattern of annual precipitation anomalies (mm) associated with moderate to strong El Niño events from 1900 to 1998 compared to normal years (after Dai and Wigley, 2000). Locations of sites with coral records discussed in text are shown by circles.

Figure 3. Comparison of satellite-derived SST (Reynolds and Smith, 1994) and in situ SST measurements at five coral coring sites: Ishigaki Island (Shiraho reef), Bicol (off Sorsogon City), Chuuk Atoll (East Channel), Pohnpei Island (Main channel), and Majuro Atoll (Central Shoal). Bold gray and thin black lines indicate weekly means of satellite-derived and in situ SSTs, respectively, for each site. In the upper panel (Ishigaki Island), the 10-day mean SST record at Ishigaki Port (daily observation at 10:00 a.m. local time) is also shown (Ishigaki-jima Meteorological Observatory, the Japan

Meteorological Agency; JMA). At Micronesian coral sites, results of 6-month-long in situ SST monitoring showed no differences with IGOSS SSTs, which indicates the accuracy of the latter. The SST in Bicol also showed excellent agreement with the IGOSS NMC SST. However, at Ishigaki Island, wintertime IGOSS NMC SSTs showed relatively large differences of up to 2°C with in situ SSTs as a result of surface cooling.

Figure 4. Coral $\delta^{18}\text{O}$ records in the western Pacific region covering about 20 years (locations of coral cores are shown in Fig. 1). Black triangles mark locations of growth perturbations identified by abrupt shifts in $\delta^{18}\text{O}$ profiles. Dates of collection are shown with arrows. Details of cores (locality, species name, time span of records) are given in the text.

Figure 5. Time-series of instrumental SSTs (bold gray line) and estimated SST based on coral $\delta^{18}\text{O}_\text{c}$ records (open circles with thin black line) from Ishigaki Island, southern Japan. A 10-day mean SST record at Ishigaki Port conducted by the JMA Ishigaki-jima Meteorological Observatory is shown as the instrumental SST time-series. SSTs were estimated by using equations (1), (2), and (3) for IU96-07, IS91-06, and IY99-01, respectively. The slope of the relationship between SST and $\delta^{18}\text{O}_\text{c}$ is shown in each profile. The coral time-series is plotted by linearly interpolating between the minima and maxima of the coral $\delta^{18}\text{O}_\text{c}$ estimates of SST.

Figure 6. Temperature dependency of the coral $\delta^{18}\text{O}_\text{c}$ signature. Bold lines indicate *Porites* spp. coral specimens from Ishigaki Island, southern Ryukyus. Specimen details (sample i.d., slope, species name, locality, original reference) are as follows: IS91-06 ($-0.140\text{‰ } ^\circ\text{C}^{-1}$, *P. lutea*, Shiraho, this study), IY99-01

($-0.148\text{‰ }^{\circ}\text{C}^{-1}$, *P. lutea*, Yasura-zaki, this study), IU96-07 ($-0.165\text{‰ }^{\circ}\text{C}^{-1}$, *P. australiensis*, Urasoko, Suzuki et al., 1999), and a *Porites* colony ($0.134\text{‰ }^{\circ}\text{C}^{-1}$, *P. lutea*, Yasura-zaki, Mitsuguchi et al., 1996). The vertical displacement of calibration lines for Ishigaki corals toward the negative can be explained by the local differences in mean $\delta^{18}\text{O}_w$ between Ishigaki Island and the other regions (Suzuki et al., 1999; 2001; Gagan et al., 1998; Leder et al. 1989; McConnaughey, 1989;).

Figure 7. Comparison of skeletal $\delta^{18}\text{O}_c$ of a Chuuk coral and instrumental records for the period between 1980 and 1999. Rainfall was observed at a NOAA station (<http://lumahi.soest.hawaii.edu/Enso/data/ftp/STATION-RAIN2/chuuk-sum.txt>), and the SOI is a standardized sea-level pressure difference (<http://ingrid.ldgo.columbia.edu/SOURCES/Indices/.soi/.standardized/>); see text for other data sources. No filter was applied to isotope data. Double arrows indicate a distinct positive shift of $\delta^{18}\text{O}_c$ in El Niño years, while single arrows indicate the compressed $\delta^{18}\text{O}_c$ curves for the year following the El Niño peak. Note that SSS is reverse-plotted so that El Niño-related anomalies vary in the same direction as the other parameters in the curve. Times-series of monthly rainfall and SOI are smoothed by a 3-month and 5-month moving average, respectively. El Niño events (warm phases) are shown by shading according to the classification by the NCEP/CPC (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html).

Figure 8. Crossplots of coral $\delta^{18}\text{O}_c$ and monthly observations of SSS (A) and SST (B). Monthly coral $\delta^{18}\text{O}_c$ time-series were resampled using AnalySeries software (Palillard et al., 1996). Months categorized as reflecting strong El

Niño conditions by the NCEP/CPC are plotted as closed circles. $SSS = 41.7 + 1.30\delta^{18}\text{O}_c$, $R^2 = 0.35$, $P < 0.01$; $SST = 16.9 - 2.11 \delta^{18}\text{O}_c$, $R^2 = 0.45$, $P < 0.01$.

The gray bar in panel B represents the temperature dependency slope for coral aragonite ($0.13\text{‰} - 0.18\text{‰ } ^\circ\text{C}^{-1}$).

Figure 9. Skeletal $\delta^{18}\text{O}_c$ records of *Porites* spp. corals from Ishigaki Island and Pandora Reef, plotted against distance from the surface of the colonies along the microsampling transects. In the topmost panels, regional weekly SSTs (NOAA NMC SSTs) are shown. The year is shown above the parts of the $\delta^{18}\text{O}_c$ curve corresponding to the $\delta^{18}\text{O}_c$ minimum in the boreal summer for Ishigaki corals, while for Pandora Reef corals, the year is shown above the austral winter. The intervals of growth discontinuity are shown by shaded vertical bars. Data are replotted from Suzuki et al. (2003).

Figure 10. Comparison of instrumental SST (solid gray curves) and *Porites* coral $\delta^{18}\text{O}_c$ values (curves with circles) from Ishigaki Island, Japan; Bicol, the Philippines; and Chuuk Atoll and Pohnpei Island, Micronesia, in the northwestern Pacific. Regional weekly SSTs (NOAA NMC SSTs) are shown for Bicol, Chuuk, and Pohnpei as instrumental SSTs while the 10-day mean SST record of the JMA Ishigaki-jima Meteorological Observatory is shown for Ishigaki Island. Coral $\delta^{18}\text{O}_c$ curves are related to “apparent” SSTs based on the $\delta^{18}\text{O}_c$ –SST relation: Ishigaki (coral specimen IU96-07), $SST = -1.4 - 5.57\delta^{18}\text{O}_c$; Bicol (SWGM01-01), $SST = 0.57 - 5.58\delta^{18}\text{O}_c$; Chuuk (CHU99-01), $SST = 8.1 - 3.60\delta^{18}\text{O}_c$; and Pohnpei (POH99-02), $SST = 10.3 - 3.43\delta^{18}\text{O}_c$. “Apparent” SSTs derived from the coral $\delta^{18}\text{O}_c$ values take into account offsets due to changes in seawater $\delta^{18}\text{O}_w$ of the region. The gray and solid lines show simple regressions

for instrumental and coral-derived SSTs, respectively. Magnitudes of the warming trend between 1981 and 2000 calculated from instrumental SST time-series and “apparent” SSTs derived from coral $\delta^{18}\text{O}_c$ values are also shown (the latter are in parentheses). Arrows mark times of severe El Niño-related drought in the region. See text for discussion.

Fig. 1 Suzuki et al.

Fig. 2 Suzuki et al.

Fig.3 Suzuki et al.

Fig. 4 Suzuki et al.

Fig.5 Suzuki et al.

Fig. 6 Suzuki et al.

Fig. 7 Suzuki et al.

Fig. 8 Suzuki et al.

Fig. 9 Suzuki et al.

Fig.10 Suzuki et al.