Last Interglacial coral record of enhanced insolation seasonality and seawater O enrichment in the Ryukyu Islands, northwest Pacific

Last Interglacial coral record of enhanced insolation seasonality and seawater ^{18}O enrichment in the Ryukyu Islands, northwest Pacific

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Abstract. We present a calibrated, high-resolution $^{18}O/^{16}O$ and $^{13}C/^{12}C$ record for a well-preserved Last Interglacial *Porites* sp. coral (U-Th age of 127 ± 6 ka) from the sea-level high-stand terrace of Yonaguni Island, Japan. Seasonal variations in the $\delta^{18}O$ and $\delta^{13}C$ values for the fossil coral are greater than those observed in modern coral records from the same reef setting and appear to be driven by the enhanced insolation seasonality in the northern hemisphere during the Last Interglacial maximum. The ^{18}O enrichment of 1.1‰ in the fossil coral compared to the modern analogue cannot be due entirely to a reduction in sea-surface temperature because corals in this region are already growing at their lower thermal limit. Instead, most of the ^{18}O enrichment must be due to a change in the $\delta^{18}O$ of the surface seawater, probably in response to enhanced evaporation of the ocean or a higher volume flux of the Kuroshio Current.

Introduction

The global climate change debate has led to renewed interest in analyzing corals that grew during times when the earth was warmer than today, or warming rapidly. Although these climates of the past are not exact analogues for a CO_2-warmed Earth, such records will certainly yield perspectives on the sensitivity of climatic processes to global climate change [*Crowley*, 1990]. Analysis of terrestrial paleoclimate data for the Last Interglacial maximum suggests that the northern hemisphere was warmer / wetter in response to higher solar insolation [*CLIMAP,* 1984; *Crowley and North,* 1991]. At the same time, stronger insolation seasonality in the northern hemisphere is thought to have driven a stronger monsoon in northern Africa and Asia, leading to warmer / wetter summers [*Klein et al.,* 1990]. However, the details of seasonal climate change during the Last Interglacial are less clear, particularly for the tropical regions.

We report a 10-year-long, high-resolution oxygen- and carbon-isotope record for a Last Interglacial coral from Yonaguni Island, Japan. Our primary aim is to document the surface-ocean hydrologic balance during this period of higher insolation seasonality in the northern hemisphere, and generally warm climates [*Prell and Kutzbach,* 1987]. Recent work has shown that even a small increase in tropical SST, on the order of 0.5°C, leads to a marked increase in oceanic evaporation and precipitable water in the atmosphere [*Flohn et al.,* 1990]. Model simulations show that the tropical hydrological cycle and latitudinal gradients in sea surface temperature (SST) may drive changes in atmospheric circulation at higher latitudes [*Rind,* 1998].

Materials and Methods

Fossil and Modern Corals

Our study was designed to compare the fossil coral isotope record with modern coral records from similar reef environments found at the same latitude (Figure 1B). The fossil *Porites* sp. coral was collected from the uplifted Pleistocene coral terrace of Yonaguni Island at 3 m above present mean sea level (MSL) and has an a-counting U-Th age of 127 ± 6 ka [*Omura et al.,* 1994]. According to current understanding, the Last Interglacial sea-level highstand persisted from 128 ± 1 to 116 ± 1 ka [*Stirling et al.,* 1998]. The fossil coral is therefore likely to record oceanic conditions during the culmination of the penultimate deglaciation. XRD analysis and microscopic examination of the coral skeleton indicate that the coral aragonite is well preserved. The δ^{234}U value of 148 ± 20‰, which is similar to the values reported for well-preserved late Pleistocene corals from other regions [e.g., *Stirling et al.,* 1998] confirms this result.

Ishigaki Island, which is located 128 km to the east of Yonaguni Island (Figure 1A), was chosen as the best site for modern coral examination because of similar environmental settings. Furthermore, *in situ* SST and direct global solar radiation data (hereafter, insolation) monitored by the Japan Meteorological Agency are available for comparison with the coral isotopic data. We were particularly careful to establish the bounds of variability experienced by corals growing in modern reef settings because the precise paleoenvironment of the fossil coral is not known. Isotopic data for a *P. australiensis* coral (IU96-07) growing at 3.5 m below MSL, and in relatively well-flushed conditions, were compared with data from a nearby SST monitoring site to derive the δ^{18}O-SST relation used in this study [*Suzuki et al.,* 1999]. Another coral (*P. lutea*, IS91-06) was collected from the bottom of a moat (2 m below MSL), in the lee of a fringing reef, to ensure that the two different reef environments produced proxy SSTs similar to the regional mean SST.

Analytical Methods

A detailed description of the isotopic data for the modern coral (IU96-07) was reported by *Suzuki et al.* [1999] (Figure 1C). Other corals were processed according to the micro-sampling procedures described by *Gagan et al.* [1994; 1998]. An average of about 50 samples per annual growth increment were collected. Isotopic analyses for these corals were obtained by reacting the aragonite with 105% H_3PO_4 at 90°C in an automated individual-carbonate reaction device coupled with a Finnigan MAT-251 mass spectrometer. The isotope ratios are reported as per mil (‰) deviations relative to the Vienna Pee Dee belemnite (VPDB).

Results and Discussion

Seasonal Changes in SST and Insolation

The two modern coral oxygen-isotope records are similar, despite the difference in their linear growth rates, and show clear annual fluctuations of oxygen-isotope ratios that match the relatively large seasonal fluctuation of SST (~10°C) observed in the instrumental SST record (Figure 2). The mean amplitude of the seasonal variation in δ^{18}O for the two records is 1.39 ± 0.20‰. In contrast, the mean amplitude of the δ^{18}O fluctuations for the fossil coral is 10% greater (1.51 ± 0.21‰) than those of the modern corals.

The seasonal variations in the δ^{13}C values for the fossil coral are also about 20% greater than those observed in the modern corals. In general, there is a negative correlation between the d^{13}C and δ^{18}O values in the two modern corals whereby the annual cycle of the d^{13}C occurs 1-2 months before that of the δ^{18}O (Figure 3B). The shift between the coral δ^{18}O and δ^{13}C cycles clearly corresponds to the 1-2 month lag between the annual cycles of instrumental SST and insolation records (Figure 3A). This suggests that solar radiation is the dominant controlling factor of skeletal δ^{13}C. The best explanation for the coral δ^{13}C variations would be the coral skeletal ^{13}C-radiant energy model [*Fairbanks and Dodge*, 1979; *McConnaughey*, 1989], which predicts that algal photosynthesis causes ^{13}C-enrichment of the internal calcification reservoir from which skeletal carbon is drawn.

The Milankovitch astronomical calculations record a 50% increase in insolation seasonality during the Last Interglacial maximum at 20°N [340 Wm^{-2} modern vs 510 W m^{-2} Last Interglacial; *Berger and Loutre,* 1991]. Thus, the enhanced seasonal contrast of the fossil coral SST and δ^{13}C range may be a response to the increased seasonal contrast in insolation. The lead-time between the seasonal δ^{13}C and δ^{18}O cycles is about 1-2 months greater (3-4 months) than for the modern corals. The longer lead-time may be due to the slow response of the ocean to the rapid seasonal change in insolation at the time.

Seawater Oxygen Isotope Composition

The mean δ^{18}O value of the fossil coral record (-4.0 ± 0.6 ‰) is ~1‰ higher than the average for the modern corals (Figure 2). This difference would correspond to a temperature decrease of ~6°C, relative to present. However, such cooling is highly unlikely because the present average winter minimum temperature of 21.7°C is close to the 18°C lower thermal limit of coral growth [*Veron and Minchin,* 1992]. Indeed, the portion of the modern coral δ^{18}O record is compressed in winter, relative to the summer, indicating that calcification rates are reduced in the winter in response to the cool SSTs [*Fallon et al.,* 1999]. Although there is the potential for the fossil coral to survive a 3.7°C cooling, the annual cycle of SST does not appear to be distorted in the coral record, suggesting that cooling of Last Interglacial winter SSTs in this region is unlikely. Negligible cooling in the Last Interglacial maximum is also consistent with the result of *CLIMAP* [1984] and the recent result base on fossil corals [*Tudhope et al.,* 2001].

The ^{18}O enrichment recorded by the fossil coral likely reflects a significant change in the δ^{18}O of seawater ($\delta^{18}O_W$), rather than a large cooling. The coral δ^{18}O-SST relation derived for this region indicates that the lower limit for coral growth of 18°C corresponds to a coral δ^{18}O value of -3.54‰. The mean δ^{18}O value for the 11 winters recorded by the fossil coral is -3.14‰. This translates to an estimated minimum shift in $\delta^{18}O_W$ of ~0.4‰ (dark stippled area in Figure 4) if average winter SSTs did indeed drop to 18°C during the Last Interglacial. More probable is that there was no cooling of SST. In that case, the present 21.7°C average winter minimum recorded by the modern corals equates to a coral δ^{18}O value of -4.23‰. Therefore, the enrichment of $\delta^{18}O_W$ could be up to

~1.1‰ (light plus dark stippled area in Figure 4), or greater, if SSTs were warmer in the far northwestern Pacific during the Last Interglacial maximum. Comparable ^{18}O enrichment is also reported for a Last Interglacial coral from Indonesia [*Hughen et al.,* 1999].

Hydrologic Balance and Ocean Circulation

As GEOSECS data clearly indicate [*Ostlund,* 1987], the salinity and $\delta^{18}O_W$ values for surface waters in the Pacific are highly correlated and, in general, the waters around 30°N are enriched in ^{18}O relative to the rest of the northern Pacific [*Broecker,* 1989]. However, $\delta^{18}O_W$ values reported for the southern Japan and Taiwan regions [0.33-0.38‰$_{SMOW}$ by *Watanabe and Oba,* 1999; 0-0.36‰$_{SMOW}$ by *Shen et al.,* in press] are relatively low compared to the GEOSECS latitudinal profile in the Pacific. This may be related to ^{18}O-depleted precipitation in the area of the Eastern China Sea, where the Kuroshio Current passes. Therefore, the Last Interglacial shift in $\delta^{18}O_W$ toward higher values could be interpreted as a reduction in precipitation and/or an increase in evaporation in the Kuroshio Current region.

Millennial-scale oscillations of the east Asian monsoon characterized by relatively dry conditions [*An and Porter,* 1997] and abrupt ~7°C cooling of equatorial western Pacific SSTs [*McCulloch et al.,* 1999] have been reported for the Last Interglacial, so it is possible that the fossil coral could be recording an anomalously cool dry period. However, a more probable condition during the Last Interglacial is the equable climates associated with slightly higher SSTs that would certainly increase evaporation at the surface ocean [*Flohn et al.,* 1990]. Changes in atmospheric circulation at this time, brought about by the enhanced insolation seasonality, and consequent changes in latitudinal temperature gradients, could have transported the extra atmospheric water vapor toward the continents to increase precipitation, as revealed by terrestrial paleoclimate records [*CLIMAP,* 1984] and a modeling study [*Prell and Kutzbach,* 1987]. The latter indicates that enhanced summer insolation forcing can intensify the sub-tropical wind-field over the ocean, which would intensify the sub-tropical gyre. The relatively saline and, presumably, ^{18}O-enriched water of the North Equatorial Current is the primary source for the poleward-flowing Kuroshio Current, which warms the coral reefs of southern Japan. An increase in regional SSTs accompanying the greater volume flux of the Kuroshio Current may have been crucial for the expansion of coral reefs to higher latitudes in the far northwestern Pacific.

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References

An, Z. and S. Porter, Millennial-scale climatic oscillations during the last interglaciation in central China, *Geology*, *25*, 603-606, 1997.

Berger, A. and M. F. Loutre, Insolation values for the climate of the last 10 million years, *Quat. Sci. Rev.*, *10*, 297-317, 1991.

Broecker, W. S., The salinity contrast between the Atlantic and Pacific oceans during glacial time, *Paleoceanogr.*, *4*, 207-212, 1989.

CLIMAP Project Members, The last interglacial ocean, *Quat. Res.*, *21*, 123-224, 1984.

Crowley, T. J., Are there any satisfactory geologic analogues for a future greenhouse warming? *J. Climate*, *3*, 1282-1292, 1990.

Crowley, T. J. and G. R. North, *Paleoclimatology*, 339 pp., Oxford University Press, New York, 1991.

Fairbanks, R. G. and R. E. Dodge, Annual periodicity of the ^{18}O/^{18}O and ^{13}C/^{12}C ratios in the coral *Montastrea annularis*, *Geochim. Cosmochim. Acta*, *43*, 1009-1020, 1979.

Fallon, S., M.T. McCulloch, R. van Woesik, and D. Sinclair, Corals at their latitudinal limits: laser ablation trace element systematics in *Porites* from Shirigai Bay, Japan, *Earth Planet. Sci. Lett.*, *172*, 221-238, 1999.

Flohn, H., A. Kapala, H.-R. Knoche, and H. Machel, Recent changes of the tropical water and energy budget and of mid latitude circulation, *Climate Dynamics*, *4*, 237-252, 1990.

Gagan, M. K., A. R. Chivas, and P. J. Isdale, High-resolution isotopic records from corals using ocean temperature and mass-spawning chronometers, *Earth Planet. Sci. Lett.*, *121*, 549-558, 1994.

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

Hughen, K. A., D. P. Schrag., S. B. Jacobsen, and W. Hantaro, El Niño during the last interglacial period recorded by a fossil coral from Indonesia, *Geophys. Res. Lett.*, *26*, 3129-3132, 1999.

Klein, R., Y. Loya, G. Svistzman, P. J. Isdale, and M. Susic, Seasonal rainfall in the Sinai Desert during the late Quaternary inferred from fluorescent bands in fossil corals, *Nature*, *345*, 145-147, 1990.

McConnaughey, T., ^{13}C and ^{18}O isotopic disequilibrium in biological carbonates: I. Patterns, *Geochim. Cosmochim. Acta*, *53*, 151-162, 1989.

McCulloch, M. T., A. W. Tudhope, T. M. Esat, G. E. Mortimer, J. Chappell, B. Pillans, A. R. Chivas, and A. Omura, Coral record of equatorial sea-surface temperatures during the penultimate deglaciation at Huon Peninsula, *Science*, *283*, 202-204, 1999.

Omura, A., K. Kodama, M. Watanabe, A. Suzuki, and Y. Ota, Tectonic history of Yonaguni Island, southwestern Ryukyus, Japan, deduced from coral reef terraces and Uranium-series dates of Pleistocene corals, *Dai-yonki-kenkyu (The Quaternary Research)*, *33*, 213-231, 1994.

Ostlund, H. G., GEOSECS Atlantic, Pacific and Indian Ocean expeditions, in *Shorebased data and graphics 7*, IDOE National Science Foundation, 1987.

Prell, W. L. and J. E. Kutzbach, Monsoon variability over the past 150,000 years, *J. Geophys. Res.*, *92*, 8411-8425, 1987.

Quinn, T. M., F. W. Taylor, T. J. Crowley, and S. M. Link, Evaluation of sampling resolution in coral stable isotope records: A case study using records from New Caledonia and Tarawa, *Paleoceanogr.*, *5*, 529-542, 1996.

Rind, D., Latitudinal temperature gradients and climate change, *J. Geophys. Res.*, *103*, 5943-5971, 1998.

Shen, C.-C., T. Lee, C.-H. Wan, K.-K. Liu, and M.-Y. Lee, Quantitative reconstruction on past precipitation records using Sr/Ca and δ^{18}O measurements in corals, *Geochim. Cosmochim. Acta*, in press.

Stirling, C. H., T. M. Esat, K. Lambeck, and M. T. McCulloch, Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral growth, *Earth Planet. Sci. Lett.*, *160*, 745-762, 1998.

Suzuki, A., I. Yukino, and H. Kawahata, Temperature-skeletal δ^{18}O relationship of *Porites australiensis* from Ishigaki Island, the Ryukyus, Japan, *Geochem. J.*, *33*, 419-428, 1999.

Tudhope, A., C. P. Chiloctt, M. T. McCulloch, E. R. Cook, J. Chappell, R. M. Ellam, D. W. Lea, J. M. Lough, and G. B. Shimmield, Variability in the El Niño-southern oscillation through a glacial-interglacial cycle, *Science*, *291*, 1512-1517, 2001.

Veron, J. E. N. and P. R. Minchin, Correlations between sea surface temperature, circulation patterns and the distribution of hermatypic corals of Japan, *Continent. Shelf Res.*, *12*, 835-857, 1992.

Watanabe, T. and T. Oba, Daily reconstruction of water temperature from oxygen isotopic ratios of a modern *Tridacna* shell using a freezing microtome sampling technique, *J. Geophys. Res.*, *104*, 20667-20674, 1999.

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Figure 1. (A) Location of coral δ^{18}O-SST calibration sites in the Pacific superimposed on rainfall patterns of Legates/MSU Precipitation Climatology [http://tao.atmos.washington.edu/legates_msu/index.html] as an indicator of δ^{18}O of seawater. The calibration sites include Ishigaki Island, Japan [*Suzuki et al.,* 1999], Nanwan Bay, Taiwan [*Shen et al.,* in press], the Great Barrier Reef [*Gagan et al.,* 1998], New Caledonia [*Quinn et al.,* 1996], and the Galapagos Islands [*McConnaughey,* 1989]. (B) Location map showing Ishigaki and Yonaguni Islands and the Kuroshio Current. (C) Comparison of northwestern Pacific δ^{18}O-SST calibrations (Ishigaki and Taiwan) and others in the Pacific.

Figure 2. Comparison of modern and fossil coral δ^{18}O and δ^{13}C records. The year corresponding to the δ^{18}O minimum in the boreal summer is indicated above the δ^{18}O curves for the modern specimens. The average skeletal extension rate and depth below MSL are indicated in the lower part of each panel. Shading indicates maximum amplitude of seasonal change in δ^{18}O.

Figure 3. (A) SST and global solar radiation observed at Ishigaki Island showing the 1-2 month difference between the annual cycles of these parameters (shaded areas). (B) Time-series of estimated SST and δ^{13}C values for a modern coral showing lag similar to that observed in the instrumental records. SSTs are estimated using T (°C) = -2.73 - 5.86 δ^{18}O [*Suzuki et al.,* 1999]. The coral time-series is plotted using a linear interpolation between the minima and maxima in the coral δ^{18}O estimates of SST. The average timing of the annual SST maximum and minimum is July 30 and February 4, respectively, as defined by the long-term average of instrumental SST record. (C) Time-series of estimated SST and δ^{13}C values for the fossil coral showing a 3-4 month lag.

Figure 4. Total estimated limits of the SST and δ^{18}O shift required to produce the 1.1‰ enrichment in the fossil coral δ^{18}O. See main text for explanation.

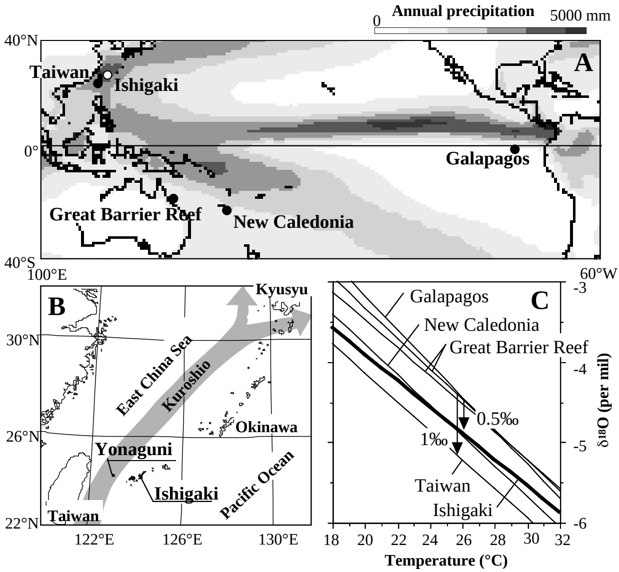
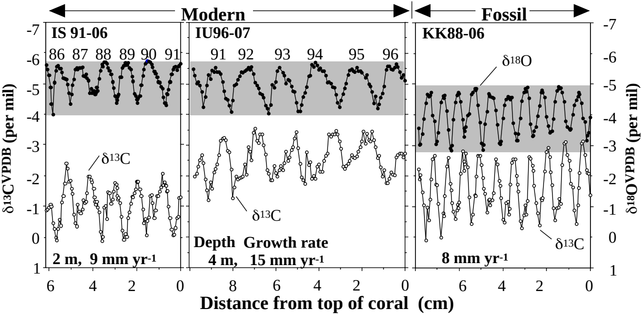

Annual precipitation
0
5000 mm
40°N
0°
40°S
100°E
60°W
A
Taiwan
Ishigaki
Galapagos
Great Barrier Reef
New Caledonia
B
Kyusyu
30°N
26°N
22°N
East China Sea
Kuroshio
Okinawa
Yonaguni
Ishigaki
Pacific Ocean
Taiwan
122°E
126°E
130°E
C
Galapagos
New Caledonia
Great Barrier Reef
0.5‰
1‰
Taiwan
Ishigaki
-3
-4
-5
-6
δ18O (per mil)
18
20
22
24
26
28
30
32
Temperature (°C)

Figure 1



Modern
Fossil
IS 91-06
IU96-07
KK88-06
86
87
88
89
90
91
91
92
93
94
95
96
δ18O
δ13C
δ13C
δ13C
Depth Growth rate
2 m, 9 mm yr-1
4 m, 15 mm yr-1
8 mm yr-1
δ13CVPDB (per mil)
δ18OVPDB (per mil)
-7
-6
-5
-4
-3
-2
-1
0
1
6
4
2
0
8
6
4
2
0
6
4
2
0
Distance from top of coral (cm)

Figure 2

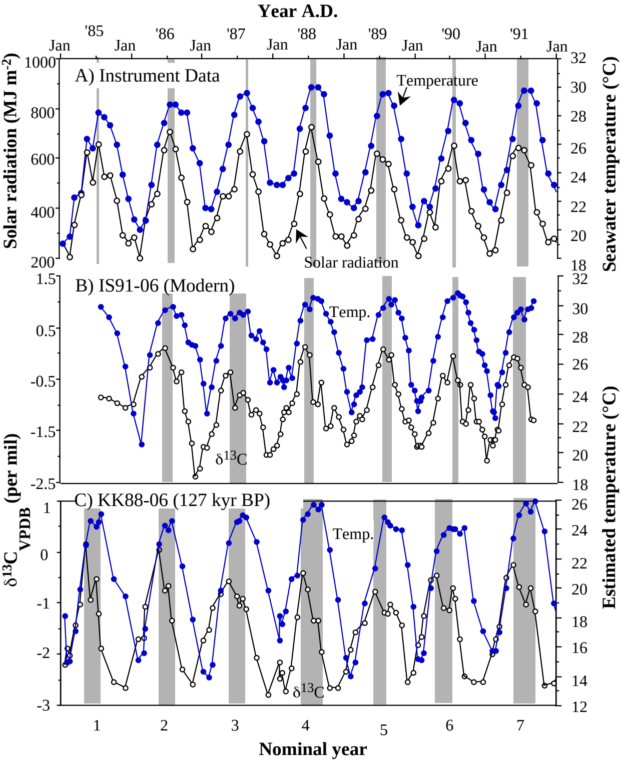

Year A.D.
'85
'86
'87
'88
'89
'90
'91
Jan
A) Instrument Data
Temperature
Solar radiation
Solar radiation (MJ m-2)
Seawater temperature (°C)
1000
800
600
400
200
32
30
28
26
24
22
20
18
B) IS91-06 (Modern)
Temp.
δ13C
1.5
0.5
-0.5
-1.5
-2.5
C) KK88-06 (127 kyr BP)
Temp.
δ13C
δ13C VPDB (per mil)
Estimated temperature (°C)
1
0
-1
-2
-3
26
24
22
20
18
16
14
12
1
2
3
4
5
6
7
Nominal year

Figure 3

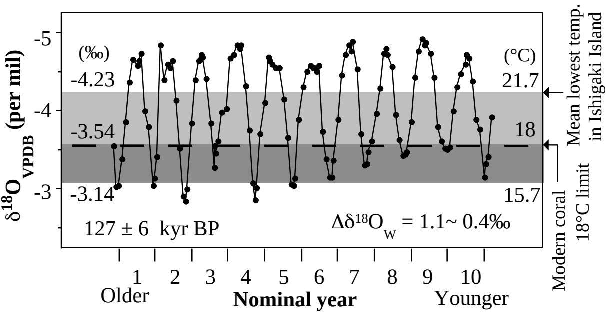

$\delta^{18}O_{VPDB}$ (per mil)
-5
-4
-3
(‰)
-4.23
-3.54
-3.14
(°C)
21.7
18
15.7
127 ± 6 kyr BP
$\Delta\delta^{18}O_W$ = 1.1~ 0.4‰
1
2
3
4
5
6
7
8
9
10
Older
Nominal year
Younger
Mean lowest temp. in Ishigaki Island
Modern coral 18°C limit

Figure 4