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Supplementary Material for

Highly Variable El Niño–Southern Oscillation Throughout the Holocene

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Materials and Methods

General description of coral cores and chronologies

Like their counterparts from Palmyra, the Christmas and Fanning fossil coral cores were drilled with a Tech2000 hydraulic drilling rig from large, exposed *Porites* coral colonies on ocean-facing beaches. Christmas Island fossil coral ‘M2’ was drilled on an expedition in 2004, and the original $\delta^{18}O$ data and SEM photos were presented in Zaunbrecher et al., 2010. Fanning modern coral A104 was collected in 1979 (some stable isotopic data from this core are presented in Druffel, 1987), but the monthly $\delta^{18}O$ data generated at SIO are presented here for the first time. The fossil corals with names beginning with a ‘V’ were drilled on Fanning in May, 2005, while corals with names beginning with a ‘P’ were drilled near the Christmas Island pier in August, 2005. The fossil corals were radiometrically dated using high-precision measurements of ^{238}U-^{234}U-^{230}Th, with errors of ±0.5-1% 2σ (Table S1). Relative chronologies were constructed by assigning the maximum $\delta^{18}O$ point for a given year to January 15th and linearly interpolating $\delta^{18}O$ datapoints in between these tie points, following the procedure outlined in Cobb et al., 2002 for the Palmyra modern and fossil corals.

Monte Carlo Significance Testing of ENSO variance changes

In order to assess the statistical significance of the observed ENSO variance difference between the Line Islands fossil and modern corals, we constructed ‘pseudocoral’ timeseries from the 2,000-yr-long NINO3.4 index from an unforced run of the GFDL CM2.1 model (Wittenberg, 2009). The first step was to determine if the distribution of interannual variance in the model timeseries is an accurate substitute for the fossil coral timeseries. To test this, we generated 10,000 different realizations of the Line Islands fossil coral database (N=990yrs of data in 21 sequences, ranging in length from 19-158 years each, see Table S2), replicating each fossil coral sequence with random segments of the model-derived NINO3.4 timeseries. The model pseudocoral segments were processed in the same way as the actual fossil coral segments. In Figure 3f, we plot the envelope of distributions of the 2-7yr variance changes for each of the 10,000 pseudocoral databases.

In order to test whether or not the observed changes in ENSO variance between subsets of the Line Islands coral database (i.e. 6-7ky versus 0-1ky (Fig. 3a and b) or 20th century versus fossil (Fig 3c and d) are significant or not, we sampled 10,000 sequences of the model data to build pseudocoral subsets. The pseudocoral subsets match the actual Line Islands coral subsets in number and length of sequences. We processed the pseudocoral data in the same way as the actual coral data, and then took the difference of the 2-7-yr variances between subsets of pseudocoral data (10,000 pairs of subsets translates to 10,000 estimates of variance differences). We then calculate the distribution of these ‘pseudocoral’ differences (Figure 3 b and d), and denote the 95% confidence threshold for significant variance differences.

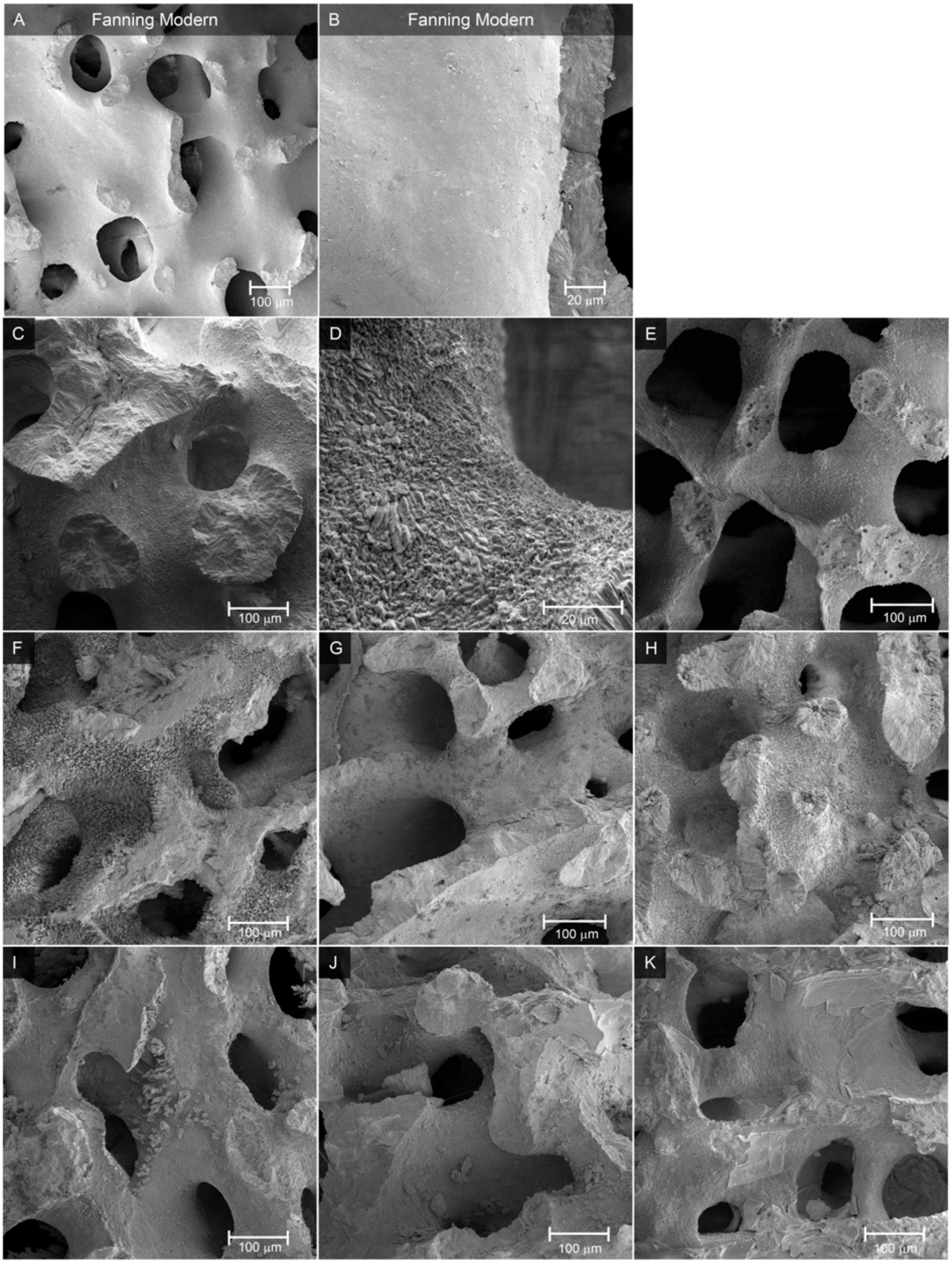

Figure S1, Plate 1. A collection of representative SEM images from Fanning Island modern and fossil corals. [Full caption under Plate 2]

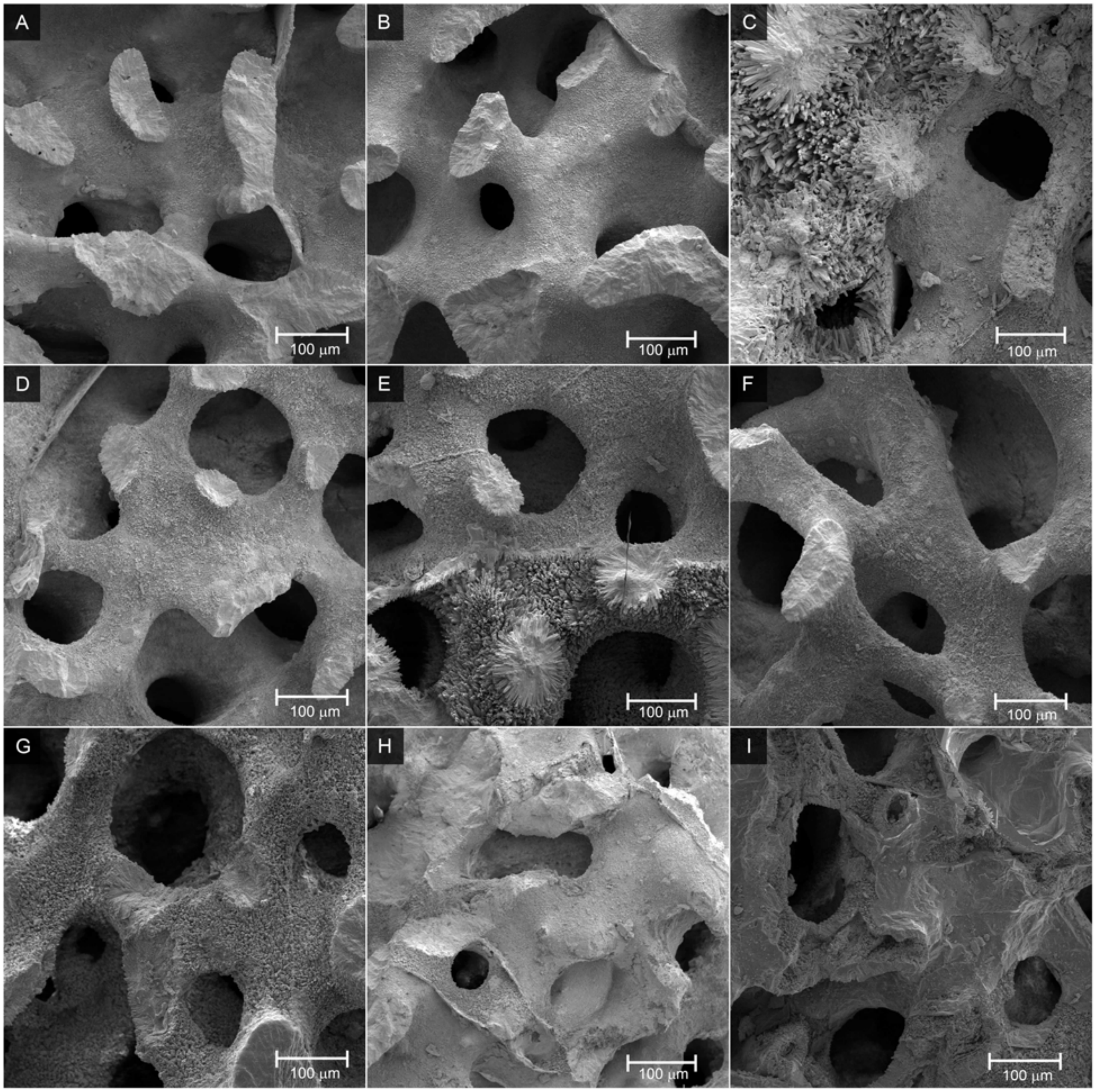

Figure S1, Plate 2. A collection of representative SEM images from Fanning Island fossil corals.
Plate 1 images: A-B: Fanning Modern, C-E: V8 (6.1ka), F-H: V10 (3.1ka), I-K: V11 (6.9ka)
Plate 2 images: A-B: V13 (6.0ka), C-D: V28 (6.4ka), E-G: V30 (6.0ka), H-I: V33 (6.6ka)
Plate 3 images: A-B: P11 (2.2ka), C-E: P26 (3.5ka), F-G: P34 (4.0ka), H: P38-1 (5.0ka), I-J: P43 (3.8ka)

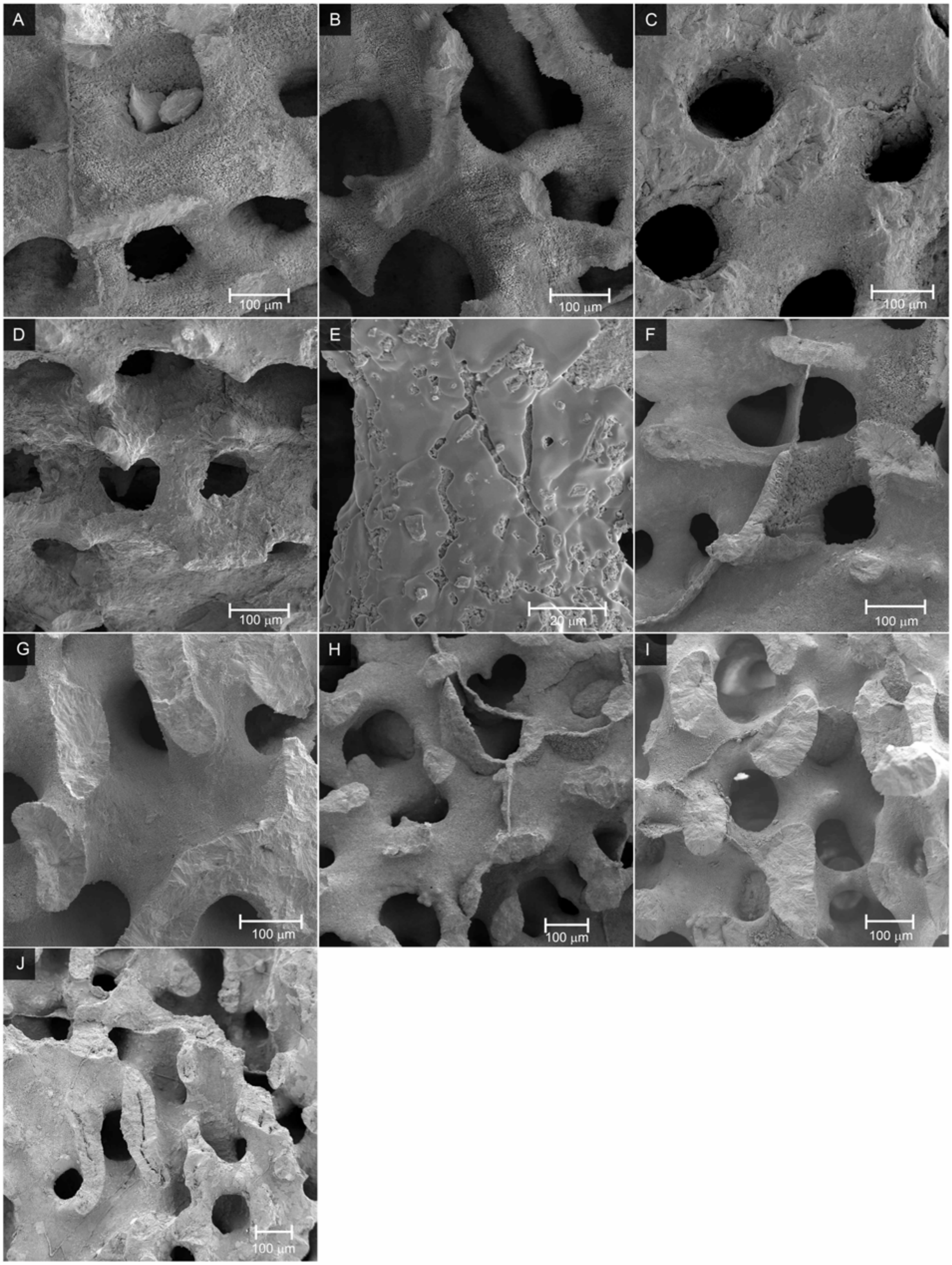

Figure S1, Plate 3. A collection of representative SEM images from Christmas Island fossil corals. [Full caption under Plate 2.]

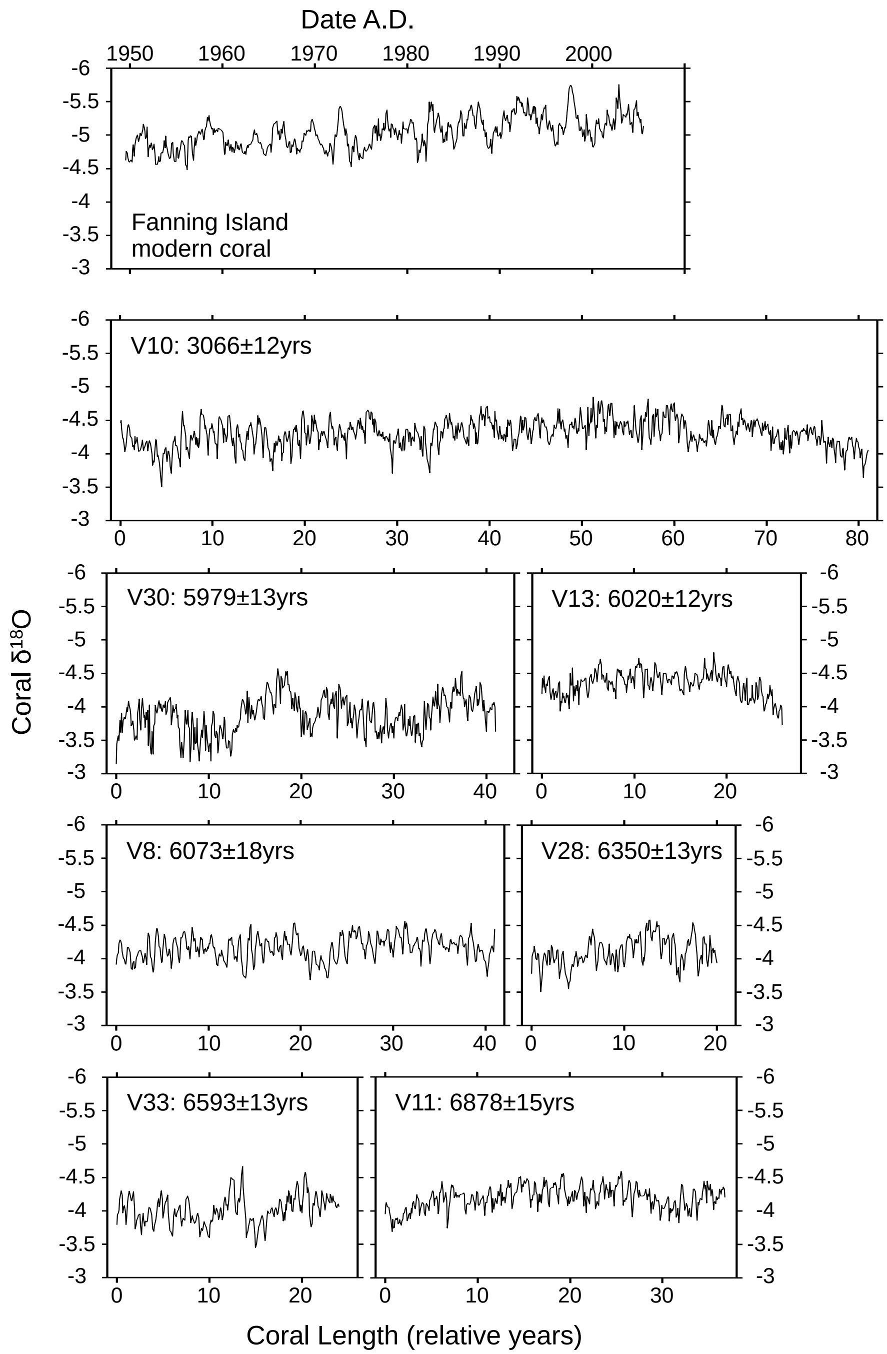

Figure S2. Plots of the raw coral $\delta^{18}O$ sequences from Fanning (this page) and Christmas (next page), shown with their respective U-series dates (see Table S1).

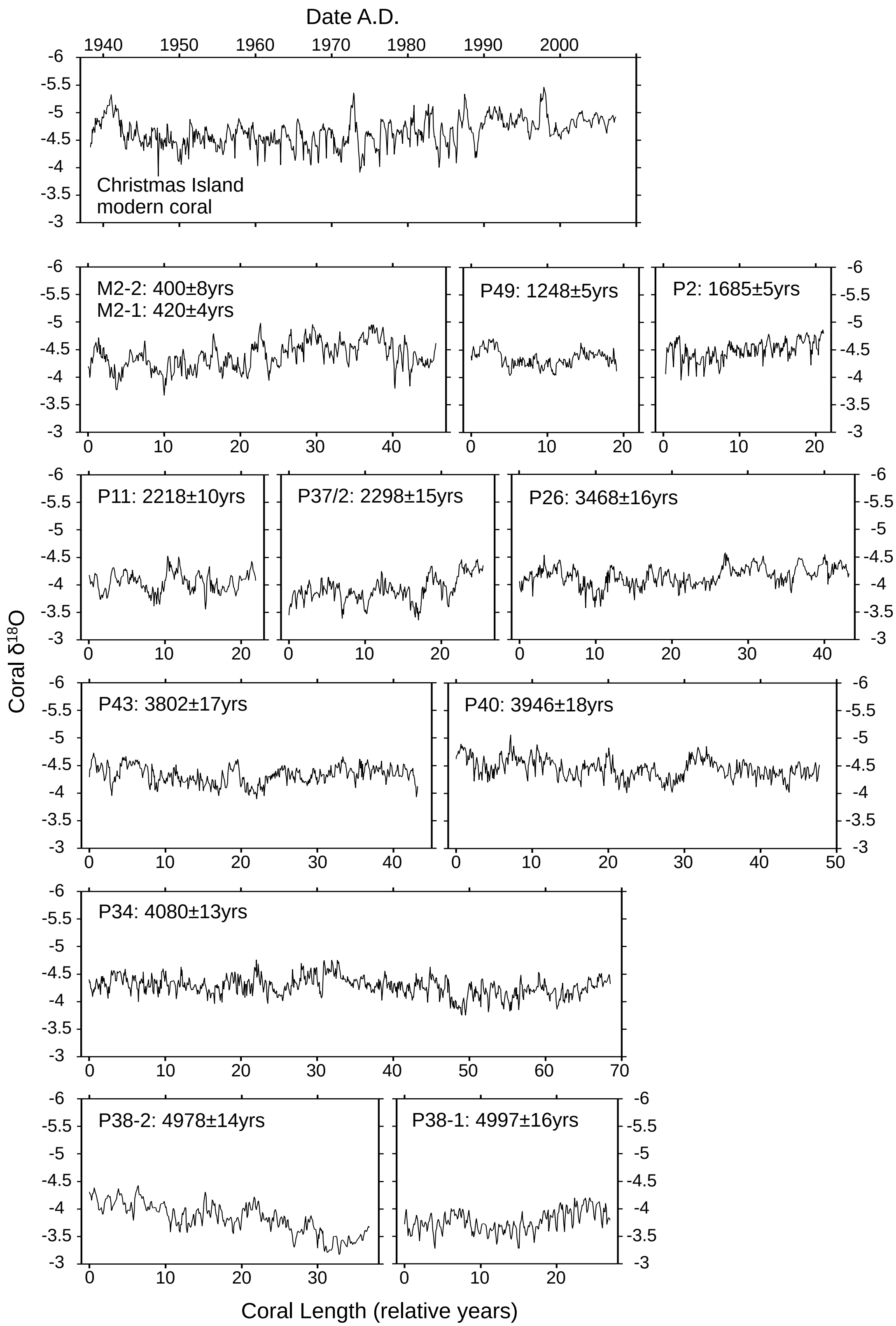

Figure S2 (cont). Plots of the raw coral $\delta^{18}O$ sequences from Christmas Island.

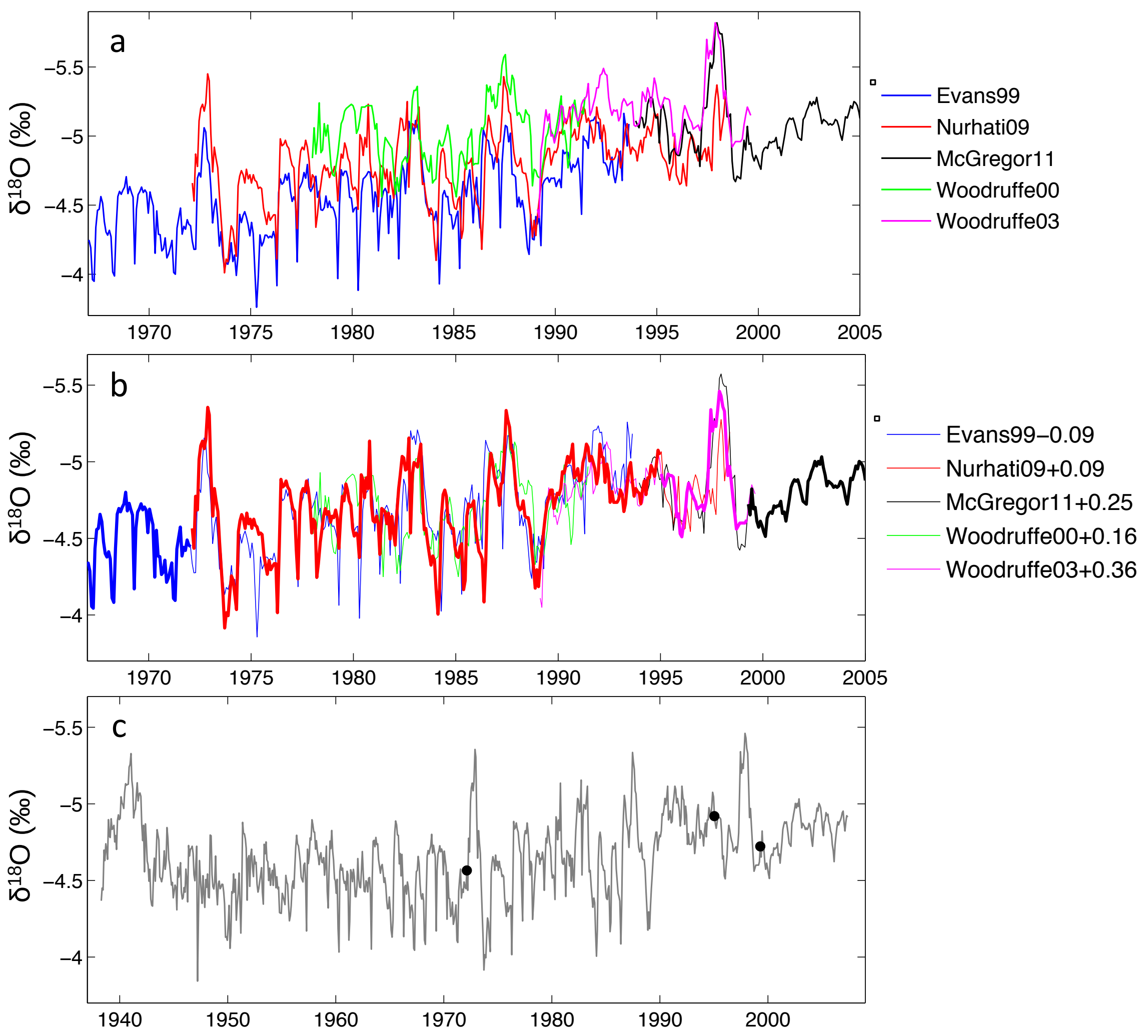

Figure S3. Construction of the Christmas Island modern coral $\delta^{18}O$ splice. **(top)** Plot of overlapping portions of original coral $\delta^{18}O$ timeseries from Evans et al., 1999 (blue), Nurhati et al., 2009 (red), Woodruffe et al., 2000 (green), Woodruffe et al., 2003 (pink), and McGregor et al., 2011 (black). All data downloaded from http://www.ncdc.noaa.gov/paleo/corals.html. **(middle)** Plot of all coral $\delta^{18}O$ records after applying offsets (in per mil; see legend) to match the mean $\delta^{18}O$ values in overlapping intervals of the records. The mean coral $\delta^{18}O$ of the composite splice was pegged to the average of the overlapping interval between the Evans et al., 1999 and Nurhati et al., 2009 records. The bold lines indicate the sections of coral that were combined to form the splice plotted in the bottom panel. **(bottom)** Plot of the resulting spliced Christmas coral $\delta^{18}O$ record, spanning from 1938 to 2007. Black circles indicate the splice points between corals.

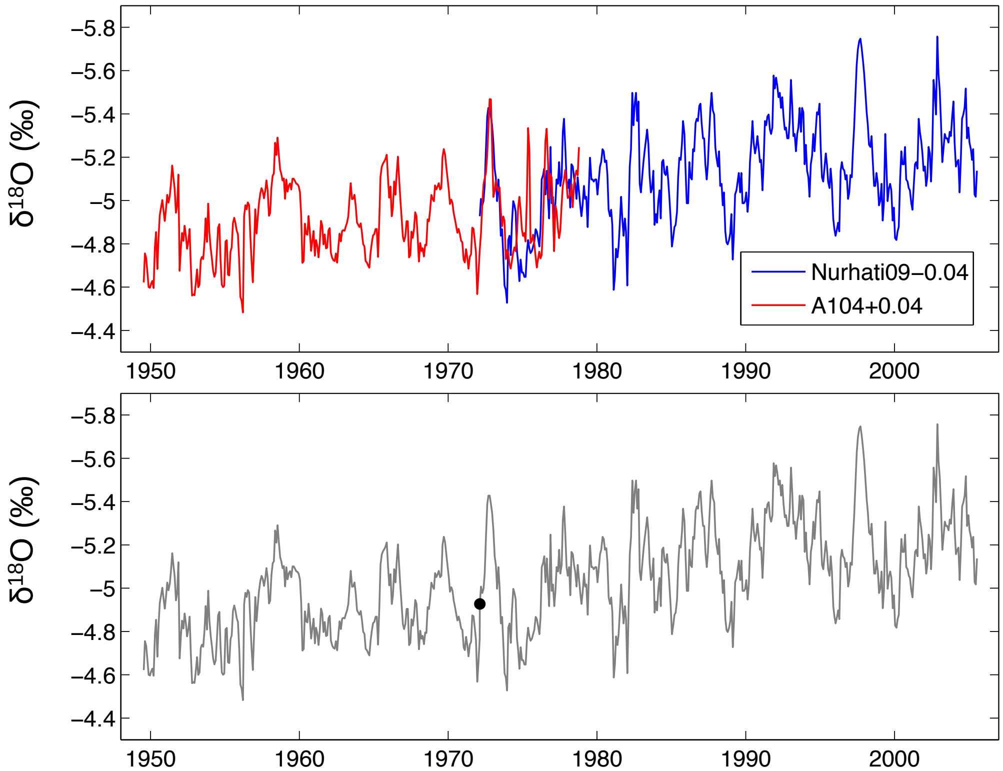

Figure S4. Construction of the Fanning Island modern coral $\delta^{18}O$ splice. **(top)** Plot of overlapping portions of original coral $\delta^{18}O$ timeseries from Nurhati et al., 2009 (red) and a new, monthly-resolved coral $\delta^{18}O$ record (red) from the 'A104' Fanning modern coral core originally presented in Druffel et al., 1987. Offsets were applied to each record to match the mean $\delta^{18}O$ values in the overlapping interval (see legend offsets in per mil). **(bottom)** Plot of the resulting spliced Fanning coral $\delta^{18}O$ record, spanning from 1950 to 2005. Black circle indicates the splice point between corals.

Table S1: U/Th dates for Line Island fossil corals presented in this study.

Sample [a]	$[^{238}U]$ [b] (ppm)	$(^{230}Th/^{238}U)$ [c] activity X 10^3	$\delta^{234}U$ (i) [d] (‰)	$[^{232}Th]$ [e] (pg/g)	^{230}Th age [f] (uncorrected) (years B.P.)	^{230}Th age [g] (corrected) (years B.P.)
M2A	2.705 ± 2.8	4.8 ± 0.08	145.4 ± 1.4	98 ± 1.1	401 ± 8	400 ± 8
M2B	2.802 ± 3.7	5.0 ± 0.04	144.7 ± 1.5	64 ± 5.7	421 ± 4	420 ± 4
P49	2.909 ± 3.6	13.7 ± 0.04	146.2 ± 1.7	63 ± 1.6	1249 ± 5	1248 ± 5
P2	2.540 ± 2.0	18.2 ± 0.05	146.3 ± 1.4	27 ± 1.4	1685 ± 5	1685 ± 5
P11	2.851 ± 3.0	23.6 ± 0.10	144.6 ± 1.4	4 ± 6.1	2218 ± 10	2218 ± 10
P37	2.830 ± 3.4	24.4 ± 0.15	145.3 ± 1.4	6 ± 4.8	2299 ± 15	2298 ± 15
V10	2.326 ± 2.5	32.3 ± 0.11	144.9 ± 1.3	511 ± 3.5	3074 ± 11	3066 ± 12
P26	2.388 ± 2.8	36.3 ± 0.16	144.5 ± 1.4	22 ± 5.3	3468 ± 16	3468 ± 16
P43	2.255 ± 3.2	39.7 ± 0.16	145.4 ± 1.7	7 ± 4.3	3802 ± 17	3802 ± 17
P40	2.474 ± 3.3	41.1 ± 0.17	144.1 ± 1.6	10 ± 5.8	3946 ± 18	3946 ± 18
P34	2.577 ± 2.9	42.5 ± 0.12	144.9 ± 1.3	12 ± 4.5	4080 ± 13	4080 ± 13
P38-2	2.874 ± 3.8	51.7 ± 0.11	146.0 ± 1.9	19 ± 1.1	4978 ± 14	4978 ± 14
P38-1	2.640 ± 2.8	51.7 ± 0.15	144.7 ± 1.3	3 ± 5.5	4997 ± 16	4997 ± 16
V30	2.759 ± 2.9	61.5 ± 0.09	142.9 ± 1.6	51 ± 1.1	5979 ± 13	5979 ± 13
V13	2.751 ± 2.8	62.2 ± 0.09	148.4 ± 1.6	44 ± 0.9	6020 ± 12	6020 ± 12
V8	2.613 ± 2.8	62.4 ± 0.16	145.0 ± 1.3	34 ± 3.3	6074 ± 18	6073 ± 18
V28	2.484 ± 2.4	65.4 ± 0.09	147.3 ± 1.6	31 ± 0.7	6350 ± 13	6350 ± 13
V33	2.439 ± 2.3	67.8 ± 0.09	147.0 ± 1.6	59 ± 1.2	6594 ± 13	6593 ± 13
V11	2.678 ± 2.9	70.7 ± 0.11	147.9 ± 1.7	20 ± 0.5	6878 ± 15	6878 ± 15

[a] A,B represent duplicate dates from different depths in the core. P38-1 and P38-2 represent two sections of the same core that were separated by a hiatus, so these were treated as two separate coral records in the reconstruction, with independent U/Th dates.
[b] All errors reported in this table are quoted as 2σ; for $[^{238}U]$, error is for last significant figure.
[c] The measured, uncorrected $(^{230}Th/^{238}U)$activity ratio; 2σ error s for last significant figure.
[d] $\delta^{234}U = \{[(^{234}U/^{238}U)/(^{234}U/^{238}U)_{eq} - 1\} \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ represents the atomic ratio at secular equilibrium; $\delta^{234}U$ (i) represents the initial value calculated using U/Th dating equations. Decay constants from Cheng et al., 2000.
[e] Corrected for a ^{232}Th total procedural blank of 7±5 pg/g.
[f] All dates are reported as years B.P. (before present), where "present" is defined as 1950 A.D.
[g] Date corrected with $(^{230}Th/^{232}Th)_{atomic}$ of 4.4 ± 2.2 x 10^{-6}, which is the value for materials at secular equilibrium, assuming a bulk Earth crustal $^{232}Th/^{238}Th$ ratio of 3.8.

Table S2. Overview of Line Islands coral records and relevant statistics.

Island	Coral Name	Date AD or Age (ka) [a]	Length (yrs)	growth rate (mm/yr)	% change in 2-7yr stdev wrt 1968-1998AD	Diagenetic condition [b]
Fanning	Modern spl	1950-2005AD	55	n/a	n/a	
	A104	1950-1978AD	28	12	n/a	
	v10	2994	81	14	-49	good
	v30	5958	42	12	-18	good
	v13	6007	27	12	-53	excellent
	v8	6056	41	10	-45	very good
	v28	6340	21	10	-22	fair
	v33	6581	25	9	-16	poor
	v11	6860	37	14	-70	good
Christmas	Modern spl	1938-2007AD	69	n/a	n/a	
	m2	1516-1561AD	45	15	-35	
	p49	1248	19	13	-57	
	p2	1684	21	20	-44	
	p11	2199	22	19	-40	good
	p37	2273	26	13	-31	
	p26	3432	42	12	-51	poor
	p43	3797	44	12	-58	good
	p40	3926	48	13	-53	
	p34	4042	68	13	-58	excellent
	p382	4941	36	9	-55	
	p381	4992	27	9	-70	excellent
Palmyra	Modern	1886-1998AD	112	18	n/a	
	NB9	1915-1937AD	22	15	-26	
	17th splice	1635-1703AD	68	8-24	-8	
	14th splice	1317-1464AD	148	7-23	-42	
	SB17	1149-1220AD	70	15	-38	
	NB12	928-961AD	32	16	-33	

[a] Note that the 'Age' reported here is the starting age for a given fossil coral d18O record, which does not necessarily correspond to the U-series age presented in Table S1, as U-series samples are typically taken from the interior of the core. Start ages were calculated by combining U-series dates from Table S1 with the relative chronology for a given core to calculate the beginning of a given fossil coral d18O record.

[b] Diagenetic condition assessed using SEM photos of fossil corals, according to the following guidelines: 'excellent' = little to no evidence of diagenetic alteration, 'very good' = some evidence of minor diagenetic alteration, 'good' = pervasive evidence of minor alteration (e.g. light surface coatings), 'fair' = isolated evidence of major alteration (thick surface coatings), and 'poor' = pervasive evidence of moderate alteration (e.g. thick surface coatings and/or dissolution)

Table S3. Modern coral date ranges chosen as benchmarks for relative modern and fossil coral ENSO variance changes plotted in Figures 2a and b.

Location	Modern Coral	benchmark interval	Reference
Line Islands	Christmas splice	1968-1998	this paper
	Fanning splice	1968-1998	this paper
	Palmyra	1968-1998	Cobb et al., 2001
Papua New Guinea	Madang	1963-1993	Tudhope et al., 2001
	Huon	1971-1995	Tudhope et al., 2001
	Liang	1963-1993	Tudhope et al., 2001
Papua New Guinea	MS-01	1967-1997	McGregor and Gagan, 2004

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