ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology 204 (2004) 115–143

PALAEO

www.elsevier.com/locate/palaeo

A strategy to improve the contribution of coral data to high-resolution paleoclimatology

J.M. Lough *

Australian Institute of Marine Science, PMB 3, Townsville MC, Qld. 4810, Australia

Received 1 October 2002; received in revised form 27 October 2003; accepted 31 October 2003

Abstract

Various geochemical tracers measured in massive coral skeletons have the potential to compliment other sources of high-resolution proxy climate information (e.g. tree rings, ice cores) by providing paleoclimatic data from shallow-water tropical ocean regions. Twenty previously published coral records (19 $\delta^{18}O$ and one Sr/Ca series), between 54 and 346 years in length, were examined for their local and larger-scale relationships (El Niño-Southern Oscillation) with climate. Series were examined in a consistent manner over the same time periods and relationships were tested for stability through time. The results demonstrate a spectrum of climatic interpretation ranging from (1) no significant relationship of the coral record with either local or larger-scale climate variables, (2) significant relationship of the coral record with climate but the relationship is not stable through time, and (3) the coral record shows a significant and temporally stable relationship with climate which explains a significant and useful proportion of climate variance. It is concluded that reliance, to date, on analyzing only one long coral core from a site has prevented identification of coral records or parts of coral records where non-climatic factors are dominating the geochemical signal. Various factors may cause these non-climatic signals to dominate. More process studies into how corals of particular species, with various growth rates and from various environmental settings incorporate geochemical tracers into their skeleton are required to understand exactly what is being measured. In addition, it is recommended that some level of replication (ideally, three separate corals) of geochemical tracers will ensure accurate dating of the record, identification of periods when non-climatic factors dominate and thus enhance the reliability of the paleoclimatic record. Such an approach will allow the rich archive of environmental information contained in massive coral skeletons to make a significant contribution to high-resolution paleoclimatology and improve our understanding of the nature and causes of past climate variability.

Keywords: coral; isotopes; paleoclimate; El Niño-Southern Oscillation; replication; sampling strategy

---

1. Introduction

Understanding the nature and causes of inter-annual, decadal and longer-term climate variability requires extension of the relatively short instrumental record of climate prior to the mid-19th century. This can be achieved through development of high-resolution, climate reconstructions from various paleoclimatic archives, e.g. tree rings, ice cores, corals and documentary sour-

---

* Fax: +61-7-47725852.
E-mail address: j.lough@aims.gov.au (J.M. Lough).

0031-0182/03/$ – see front matter Crown Copyright © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0031-0182(03)00727-2

ces. Reliable reconstructions of climate help constrain the possible range of local climate variability. Such records are also increasingly being applied to develop larger-scale hemispheric and global climate reconstructions from a particular type of proxy (Evans et al., 1998a, 2000, 2001, 2002; Briffa et al., 2001) and from a range of different proxy sources over the past several centuries (Mann et al., 1995, 1998, 1999; Jones et al., 1998; Fisher, 2002; Mann, 2002; Mann and Jones, 2003). Such multi-proxy climate reconstructions have provided the basis for determining the unusual warmth of the late 20th century with respect to the past millennium and provide supporting evidence for anthropogenic impacts on climate due to the enhanced greenhouse effect (Crowley, 2000; Houghton et al., 2001; Jones et al., 2001).

Potential sources of proxy climate information are biological, geological or human systems that (a) are influenced by climate, (b) preserve a record of that influence, (c) provide a record that can be accurately dated, and (d) provide a record that can be quantified and has a clear and consistent climatic interpretation. There are, however, no perfect proxy climate records as any source of such information will contain bias and error terms unrelated to climate. The goal, therefore, is to develop significantly calibrated and verified reconstructions of relevant climate indices which are accurately dated, of known reliability and for which the seasonality and frequency responses can be clearly identified (Briffa, 1995). Sufficient understanding of the mechanisms by which the record was formed allows development of routine principles and procedures for sampling, measuring and interpreting the data. In addition, analysis of multiple samples (replication), as routinely undertaken in dendroclimatology, ensures that common environmental signals rather than local 'noise' are interpreted. Without such replication a level of uncertainty in the data, which may overshadow the climatic interpretation, remains (Cook, 1995).

Multi-proxy climate reconstructions can, however, only be as reliable as the included data. In some instances published 'calibrations' are little more than visual assessments of similarity between observed and proxy series or matching of annual cycles in the observed and proxy series. The latter approach can clearly lead to an inflated assessment of the climatic significance of a particular proxy as any two annual cycles will have a high degree of common variance regardless of any causal link. This lack of consistent assessment of the reliability of particular proxies (most especially records from ice cores and corals) has led to some debate about the relative importance of proxy records capturing local climatic significance vs. regional or larger-scale climatic significance (Barnett et al., 1999; see responses Bradley et al., 2000; Barnett and Jones, 2000; Mann, 2002).

Massive coral skeletons, which may include several hundreds of years of continuous coral growth, contain a range of geochemical tracers which potentially provide an invaluable archive of past climates and environments for shallow-water tropical ocean regions (see reviews by Dunbar and Cole, 1999; Gagan et al., 2000; Felis and Patzold, 2003). A growing number of geochemical records measured in corals are made available to the research community through the NOAA-Paleoclimatic Data Center A (http://www.ngdc.noaa.gov/paleo/). The majority of these series are based on $\delta^{18}O$ measurements in coral skeletons. $\delta^{18}O$ in coral skeletons varies as a function of temperature and $\delta^{18}O$ of seawater. The latter is influenced by the hydrologic balance involving precipitation, evaporation, advection of water masses and freshwater runoff. In oceanic settings where $\delta^{18}O$ is constant, $\delta^{18}O$ in coral has a strong temperature dependence. In regions where the hydrologic balance dominates, $\delta^{18}O$ in coral skeletons may reflect sea surface salinity, rainfall or runoff (see reviews in Gagan et al., 2000; Felis and Patzold, 2003). $\delta^{18}O$ in coral skeletons may also reflect a combination of these two sources of variation in isotopic fractionation (Le Bec et al., 2000). The Sr/Ca ratio in coral skeletons is considered to be a more direct measure of water temperature than $\delta^{18}O$, with negligible effects of $\delta Sr/Ca_{seawater}$ over inter-annual to centennial time scales (Beck et al., 1992; Alibert and McCulloch, 1997; Gagan et al., 1998). Combined measurements of $\delta^{18}O$ and Sr/Ca have also allowed separation of the temperature component of $\delta^{18}O$ with the residual considered to reflect sea surface salinity (McCulloch et al., 1994; Gagan et al., 1998).

Although initially geochemical records in corals were considered to be fairly straightforward climate proxies there is a sense of disquiet that maybe all that looks like climate is not climate. There have also been several suggestions that potential coral proxy records should be treated with the same rigor as tree-ring records (Briffa, 1995; Cook, 1995; Crowley et al., 1999; Trenberth and Otto-Bliesner, 2003). 'Failure to test proxy coral calibrations against an independent data set could conceivably lead to erroneous conclusions about the nature and magnitude of past climate change' (Crowley et al., 1999, p. 605). Such critical assessment of potential proxy climate records is especially necessary with their increased availability and application in developing multi-proxy climate reconstructions.

Establishing the climatic interpretation of individual coral records has commonly involved a variety of statistical (and sometimes non-statistical) comparisons with available local and remote climate variables (see Appendix). An implicit assumption of many studies is that the variations measured in a single coral record can entirely be explained by one or more climatic variables. There have, however, been only a few attempts to quantify the reliability of these interpretations by comparing records obtained from different corals from the same site (Guilderson and Schrag, 1999; Linsley et al., 2000b); comparing records obtained from different coral sites (Urban et al., 2000; Hendy et al., 2002); and by global-scale comparisons of coral records and instrumental observations (Evans et al., 2000, 2001, 2002). Although the results of these studies are encouraging, close reading still suggests room for improvement in quantifying the reliability of the climatic interpretation of coral records. In addition, reliance on measurements from a single coral core assumes that the coral has a consistent climatic response throughout its lifetime. Coral growth parameters (extension, density and calcification) show considerable variability between corals living at similar locations and over time (Lough and Barnes, 2000). It would seem highly unlikely that such variability does not, in some way, impact on other parameters measured in coral skeletons (Grottoli, 2002). Many analyses of geochemical tracers in corals do not consider possible effects of growth rate changes on the recovered record. Although it has been suggested that this effect is negligible for corals with fast and steady growth rates sampled along a major growth axis (McConnaughey, 1989a,b), it is a potential source of error as few long coral cores are extracted which show these characteristics along their full length.

The ultimate goal of all paleoclimatic research is to develop accurately dated climate reconstructions of known, quantifiable and consistent reliability. The present study attempts to contribute to this goal by examining the climatic interpretation and reliability of several published coral records with at least annual resolution. The various records are analyzed in a similar manner to assess their local and/or larger-scale climatic significance and the stability of any identified relationships with instrumental climatic records. The approach is similar to Evans et al. (2000) in that comparisons are made between coral records and local and larger-scale climatic indices. The present study expands upon this earlier work by using a larger number of coral records (including Sr/Ca), comparing the coral records to both sea surface temperature (SST) and salinity and considering changes in the relationship between the coral record and climate over time.

The following questions are addressed:

- Can published coral records be interpreted as reliable proxies for inter-annual and decadal climate variability?
- How well are observed linear trends and extremes in tropical SSTs captured by published coral records?
- Can published coral records reliably reconstruct El Niño-Southern Oscillation (ENSO) variations?

2. Materials and methods

2.1. Coral records

Twenty annually or sub-annually resolved coral records (Fig. 1) between 56 and 346 years in

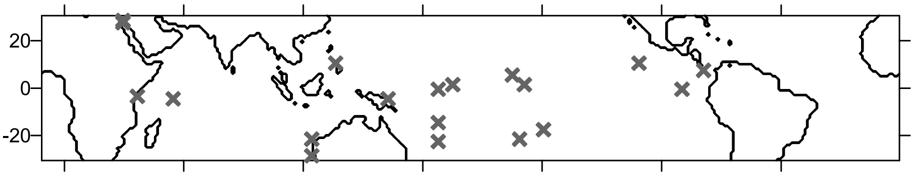


Fig. 1. Locations of 20 coral sites.

length were identified (with two exceptions, Patzold, 1986; Boiseau, 1998) from the WDC-A Paleoclimatology database (http://www.ngdc.noaa.gov/paleo/data.html). As the focus of this study was on annual and decadal variability two long published coral series with biannual (Druffel and Griffin, 1993) and 5-year resolution (Hendy et al., 2002) were not considered. Two $\delta^{18}O$ series were available from the same coral in the Gulf of Aqaba (Heiss, 1994). To ensure compatibility with the other data series, data from the Aqaba core taken from the top of the coral colony (i.e. the vertical growth axis) were used here rather than the series from the core taken horizontally. With one exception, Linsley et al.'s (2000a) Sr/Ca series, the records were measurements of stable oxygen ($\delta^{18}O$) isotopes. Coral $\delta^{18}O$ series were available for two different corals from Nauru Island (Guilderson and Schrag, 1999). The authors suggest that both corals are contaminated in their older sections by kinetic overprints: prior to 1896 for Nauru 1 and prior to 1939 for Nauru 2. Comparisons (not shown) of standardized time series for the two corals suggested that they were in agreement after 1925. The correlation between the two series was 0.02 prior to 1925 and 0.87 subsequent to 1925. This was also confirmed by correlations with local SSTs. Nauru 1 and Nauru 2 were not significantly correlated with SSTs prior to 1925 ($r = 0.06$ and 0.13, respectively) but were significantly correlated with SSTs for the period post 1925 ($r = -0.71$ and -0.64, respectively). Correlation of the average coral series with SSTs was significant ($r = -0.70$). Thus, although having two coral records did not improve the strength of the relationship with climate, having access to two records helped highlight the area of disagreement. Nauru 1 $\delta^{18}O$ was used in subsequent analyses for the period 1925–1994.

Eleven of the data sets also provided stable carbon isotope ($\delta^{13}C$) measurements (Table 1). The sampling resolution of the series varied between 1 and 12 samples per year. The original age assignments provided by the authors were used throughout. With the exception of the Tarawa Atoll series (Cole et al., 1993) which combines records from two cores from the same coral, all series were based on analysis of a single core from a single coral head. The sampled corals come from depths between 0.2 m (Madang) and 18 m (Raratonga). For 16 of the 20 series the main climatic interpretation of the isotopic measurements is SSTs and the majority of the series are also suggested to contain information about ENSO events (Table 1). Further details of the coral series and the authors' original climatic interpretations are provided in an Appendix.

2.2. Climatic and environmental records

Monthly SSTs for the 1° latitude by 1° longitude box closest to each coral site were extracted from the HadlSST1 global SST compilation which provides data for the period 1871–1999 (Rayner et al., 2003). Where available, monthly rainfall for the nearest 2.5° by 3.75° box was extracted from the Global Land Precipitation data set (gu23wld0098.dat, Version 1) developed by Mike Hulme of the Climatic Research Unit, UK (www.cru.uea.ac.uk/~mikeh/datasets/global/; Hulme, 1992). Where available, monthly salinity for the nearest 2° latitude by 10° longitude grid box was extracted from the IRD gridded Pacific salinity database, 1969–1995 (http://www.ird.nc/ECOP/notcd/general.htm; Delcroix et al., 2001).

As several of the coral records were considered to provide information about ENSO, monthly values of the Tahiti–Darwin Southern Oscillation

Table 1
Details of coral data and sources

Location	Latitude	Longitude	Depth (m)	Growth rate (mm)	Period	Values per year	Coral variable	Climate variable
Aqaba, NW Red Sea[a]	29.4°N	35.0°E	4.5	12.5	1788–1992	1	$\delta^{18}O$, $\delta^{13}C$	SST
Egypt, N Red Sea[b]	27.8°N	34.3°E	5.5	10.0	1751–1995	6	$\delta^{18}O$	SST, salinity, rainfall, NAO, ENSO, PDO
Cebu, Philippines, W Pacific[c]	10.3°N	124.0°E	?	13.3	1859–1980	1	$\delta^{18}O$, $\delta^{13}C$	SST
Clipperton Atoll, E Pacific[d]	10.3°N	109.2°W	8.2	25.0	1894–1993	12	$\delta^{18}O$, $\delta^{13}C$	SST, salinity, ENSO, PDO
Secas Is, E Pacific[e]	8.0°N	82.1°W	3	?	1708–1983	10	$\delta^{18}O$, $\delta^{13}C$	Rainfall, ITCZ
Palmyra Is, central Pacific[f]	5.9°N	162.1°W	10	20.0	1886–1997	12	$\delta^{18}O$	SST, rainfall, ENSO
Kiritimati Is, central Pacific[g]	2.0°N	157.3°W	9	?	1939–1992	12	$\delta^{18}O$, $\delta^{13}C$	SST, ENSO
Maiana Atoll, W Pacific[h]	1.0°N	173.0°E	6	9.5	1840–1993	6	$\delta^{18}O$	SST, rainfall, ENSO
Tarawa Atoll, W Pacific[i]	1.0°N	172.0°E	2–4	?	1894–1989	12	$\delta^{18}O$	ENSO
Galapagos Is, E Pacific[j]	0.4°S	91.2°W	?	13.0	1607–1952	1	$\delta^{18}O$	SST, ENSO
Nauru Is, W Pacific[k]	0.5°S	166.0°E	14	?	1897–1994	4	$\delta^{18}O$, $\delta^{13}C$	SST, salinity
Malindi, Kenya, W Indian Ocean[l]	3.0°S	40.0°E	6	12.0	1801–1994	1	$\delta^{18}O$	SST
Seychelles, W Indian Ocean[m]	4.6°S	55.8°E	7	?	1847–1994	12	$\delta^{18}O$	SST
Madang, PNG, W Pacific[n]	5.2°S	145.8°E	0.2	10.0	1923–1990	4	$\delta^{18}O$	Rainfall, ENSO
Vanuatu, SW Pacific[o]	15.0°S	167.0°E	1	8.0	1807–1978	4	$\delta^{18}O$, $\delta^{13}C$	SST, salinity
Moorea, S Pacific[p]	17.5°S	149.8°W	5	12.2	1852–1989	2–10	$\delta^{18}O$, $\delta^{13}C$	SST, ENSO
Raratonga, S Pacific[q]	21.5°S	159.5°W	18.3	?	1727–1996	12	Sr/Ca	SST, PDO
Ningaloo Reef, E Indian Ocean[r]	21.9°S	114.0°E	3	12.0	1879–1994	6	$\delta^{18}O$, $\delta^{13}C$	SST
New Caledonia, SW Pacific[s]	22.5°S	166.5°E	3	10.0	1658–1992	4	$\delta^{18}O$, $\delta^{13}C$	SST
Houtman Abrolhos Is, E Indian Ocean[t]	28.5°S	113.8°E	5	?	1795–1993	6	$\delta^{18}O$, $\delta^{13}C$	SST

[a] Heiss (1994), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1995-014.
[b] Felis et al. (2000), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2000-067.
[c] Patzold (1986), original data from Patzold (1986).
[d] Linsley et al. (2000b), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2000-048.
[e] Linsley et al. (1994), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1998-017.
[f] Cobb et al. (2001), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2001-043.
[g] Evans et al. (1998b, 1999), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1998-035.
[h] Urban et al. (2000), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2000-063.
[i] Cole et al. (1993), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1993-014.
[j] Dunbar et al. (1994), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1994-013.
[k] Guilderson and Schrag (1999), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1999-042.
[l] Cole et al. (2000), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2000-050.
[m] Charles et al. (1997), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1997-032.
[n] Tudhope et al. (1995), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1998-019.
[o] Quinn et al. (1993, 1996a), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1994-014.
[p] Boiseau et al. (1998), original data from Boiseau (1998).
[q] Linsley et al. (2000a), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2000-065.
[r] Kuhnert et al. (2000), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 2001-080.
[s] Quinn et al. (1998), IGBP Pages/WDC-A for Paleoclimatology Contribution Series # 1999-003.

Index (SOI; 1866–2000) were also used. A reconstruction of sea-level pressure (SLP) at Madras, 1796–2001 (Allan et al., 2002) was also used as an independent measure of past ENSO activity.

2.3. Analyses

Relationships between average annual values of $\delta^{18}O$ and SST were examined for 19 of the 20 sites (excluding Raratonga) over the common period, 1931–1960. Similar comparisons were also undertaken for 12 Pacific sites for which both SST and salinity data were available.

The 20 coral records covered a range of time periods with temporal resolution varying from a single annual value to 12 'monthly' values. There was also a range of climatic interpretations with different local, regional and large-scale data sets, again based on various time periods (see Appendix). One of the aims of this study was to compare the quality and reliability of the different published data sets. This needed to be undertaken in a consistent manner to allow meaningful comparisons of the different series. It was, therefore, decided to examine primarily annual variations so series with sub-annual resolution were averaged to give annual values. For series with sub-annual resolution, relationships with climatic variables were also examined for the annual maximum and annual minimum values considered separately.

Although absolute values of the various isotopic indices are important, particularly with reference to assessing climate conditions in coral records from the more distant past (e.g. Tudhope et al., 2001), further comparisons were considered beyond the scope of the present study. Each series was, therefore, standardized with respect to the mean and S.D. of the 30-year period 1931–1960 which was common to nearly all the coral records. Only the Galapagos Island coral had a slightly shorter base period, 1931–1953. The various instrumental series were also averaged to form annual values and standardized to the same common time period.

Series were filtered with a 10-year Gaussian filter to emphasize decadal variability and cross-correlation analysis over different periods was used to assess the strength and stability of relationships between variables. For annual series, the degrees of freedom used to assess significance of correlation coefficients were adjusted to allow for first order autocorrelation in the two series (Quenouille, 1952). For 10-year filtered series, the degrees of freedom used to assess significance of the correlation coefficients were approximated as the number of years divided by the filter length.

To examine how well instrumental SSTs and the coral records were able to reconstruct the SOI, principal component analysis (PCA) was performed on the following data (standardized annual anomalies) groupings:

1. Instrumental SSTs at 14 sites, 1939–1978 (SST14)
2. Coral records at 14 sites, 1939–1978 (Coral14)
3. Instrumental SSTs at eight sites, 1871–1978 (SST8)
4. Coral records at eight sites, 1852–1978 (Coral8)
5. Instrumental SSTs at five sites, 1871–1978 (SST5)
6. Coral series at five sites, 1807–1978 (Coral5)

The 14 sites were those with coral data available for the common period, 1939–1978; the eight sites were a subset of the 14 with coral data available for the period 1852–1978; and the five sites were a further subset with coral data available back to 1807. The first two principal components (PCs) from each analysis were then used in a multiple regression to predict annual values of the SOI for the period 1939–1978. Estimates of the SOI were derived for the longer periods and the calibrations verified against the SOI and also the long Madras SLP series (Allan et al., 2002).

3. Results

3.1. $\delta^{18}O$, SST and salinity

Average $\delta^{18}O$ at the 19 sites was significantly inversely related to average annual SST (Fig. 2a) with, as expected, warmer SSTs associated with more depleted $\delta^{18}O$ values. The regression suggested a temperature dependence for $\delta^{18}O$ of

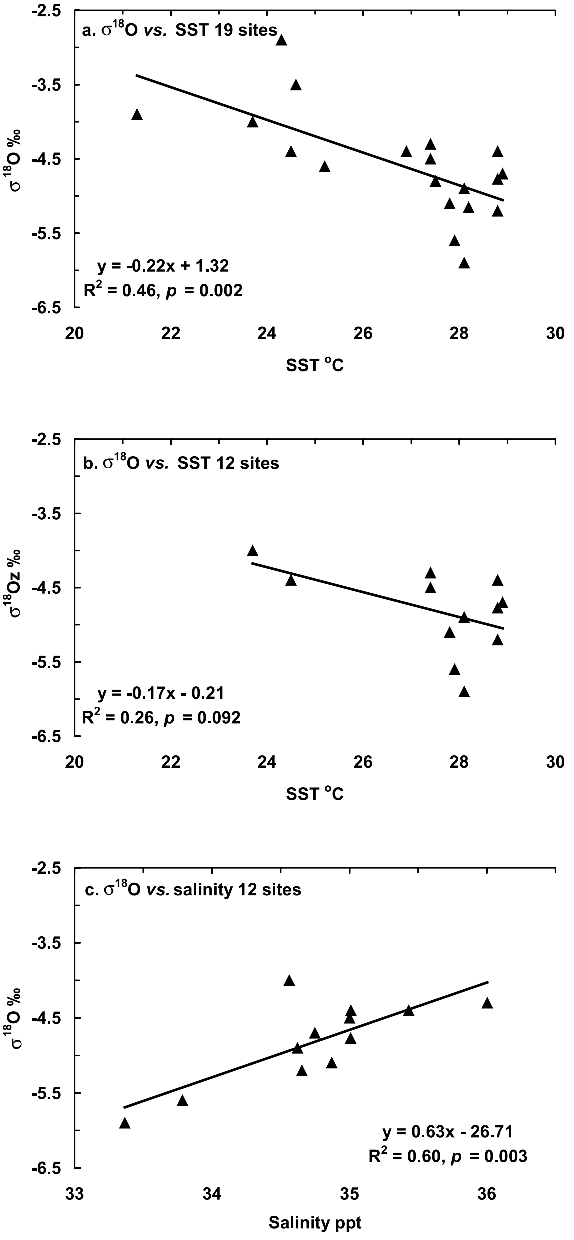


Fig. 2. (a) Average δ^{18}O vs. average SST for 19 sites, (b) average δ^{18}O vs. average SST for 12 sites, and (c) average δ^{18}O vs. average salinity for 12 sites.

−0.22 ‰ per °C. This was slightly higher than the often-quoted value for *Porites* spp. (17 of the 19 corals were *Porites* and removing Galapagos (*Pavona*) and Vanuatu (*Platygya*) from the analyses did not alter the slope) of −0.18 ‰ per °C (Gagan et al., 1994) and a mean based on 10 corals of −0.20 ‰ per °C (Evans et al., 2000; Juillet-Leclerc and Schmidt, 2001). These studies report, however, ranges at individual sites from −0.10 to −0.34 ‰ per °C.

For 12 sites in the Pacific for which both SST and salinity records were available, there was no significant relationship between average δ^{18}O (Fig. 2b) and average SST although the slope of the regression was similar to that found for the 19 sites (Fig. 2a). Average δ^{18}O was, however, significantly related to average annual salinity (Fig. 2c). Annual average SST and salinity at the 12 sites were not significantly related ($R^2 = 0.04$, $p = 0.54$). A multiple regression of SST and salinity against δ^{18}O for these 12 sites accounted for 74% of the variance in δ^{18}O (df = 2,9; $F = 12.99$, $p = 0.002$).

Inter-annual variations of δ^{18}O, SST and salinity were compared for 10 of the 11 Pacific sites for which there were sufficient years of data for meaningful comparisons (Table 2). Annual variations of δ^{18}O were significantly correlated with annual salinity variations at only four sites (Palmyra, Maiana, Tarawa and Nauru). Annual salinity and SSTs were also significantly correlated at these four sites. Partial correlations, allowing for the covariation of SST and salinity, showed that only at Nauru inter-annual variations of salinity and coral δ^{18}O were significantly correlated.

3.2. *Comparison of annual coral series with annual SST, rainfall, SOI and salinity*

Annual and decadal (10-year Gaussian filter) variations of the 20 coral series and local SSTs showed a range in the level of agreement (Fig. 3). Sixteen of the series showed significant (at the 5% level) correlations between the annual coral series and annual SST series over all available overlapping years. The magnitude of these significant correlations varied from −0.22 (< 5% common variance) for the Philippines and Secas coral series to −0.72 (52% common variance) for the Palmyra coral series. For four coral series (Aqaba, Madang, Vanuatu and Moorea), there was no significant correlation between the annual coral series and local SSTs. Decadal variations in only four coral series (Palmyra, Nauru, Seychelles and

Table 2
Correlations between annual $\delta^{18}O$ coral series, annual salinity and annual SST at 10 coral sites for specified years

Coral site	$\delta^{18}O$:salinity	$\delta^{18}O$:SST	Salinity:SST	Years
Clipperton Atoll	−0.07	**−0.59**	−0.04	1969–1993
Secas Is	0.25	−0.01	0.22	1969–1983
Palmyra Is	**0.54** (0.08)	**−0.92 (−0.88)**	**−0.62**	1969–1995
Kiritimati Is	−0.13	**−0.80**	−0.08	1969–1992
Maiana Atoll	**0.57** (0.17)	**−0.81 (−0.71)**	**−0.61**	1969–1993
Nauru Is	**0.86 (0.74)**	**−0.79 (-0.58)**	**−0.66**	1969–1994
Tarawa Atoll	**0.45** (0.22)	**−0.58 (−0.46)**	**−0.51**	1969–1989
Madang	−0.06	0.07	0.11	1969–1990
Moorea	0.41	**−0.50**	−0.43	1969–1989
New Caledonia	0.39	−0.33	−0.23	1969–1992

Values in bold are significant at the 5% level after adjusting degrees of freedom for lag 1 autocorrelation. Values in parentheses for Palmyra, Maiana, Tarawa and Nauru are partial correlation coefficients allowing for the inter-correlation of the other two variables.

New Caledonia) were significantly correlated with decadal SST variations.

The correlations presented in Fig. 3 were based on all years common to both the coral and local SST record. To test for stability of relationships through time and also provide comparable correlations for the same time periods, the relationships between the coral and climatic indices were examined for four 30-year sub-periods from 1871–1900 through 1961–1990 (Table 3). These correlations also provided an indication as to whether SSTs at a particular site showed a significant and stable relationship with ENSO (as measured by the SOI). The instrumental SST data itself may be flawed (e.g. Hurrell and Trenberth, 1999) and this could compromise the coral:SST relationships when examined through time. If, however, SSTs at a particular site were consistently and significantly related to the SOI, then it would be expected that a similar relationship would hold for the coral:SOI relationship, provided the coral record was reliably and consistently recording environmental conditions.

From the calculated relationships between coral records and local SSTs, the corals could be divided into three groups (see Table 3):

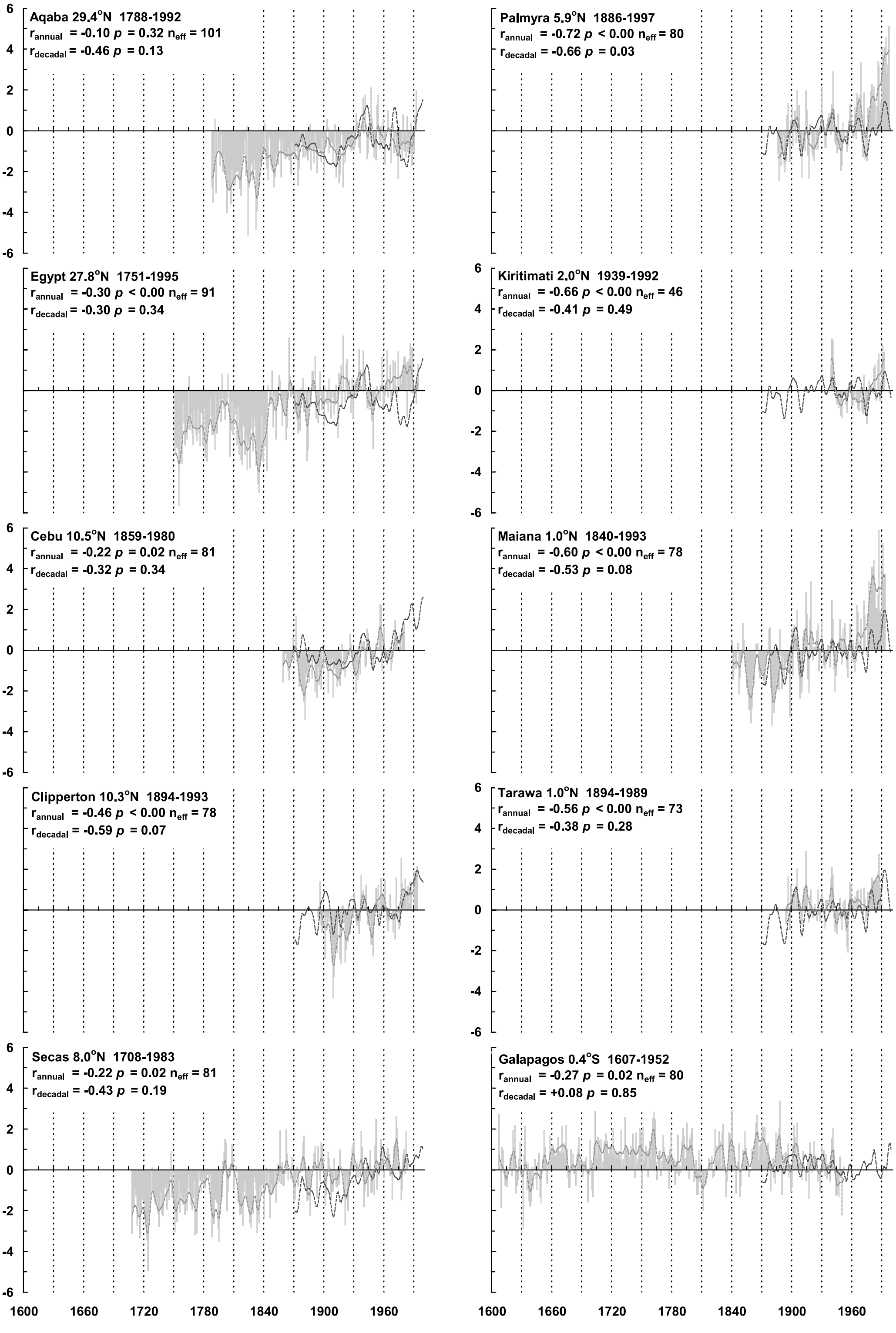
- Those records with no significant correlation with local SSTs during any 30-year sub-period: Aqaba, Secas, Madang and Vanuatu.
- Those records which were significantly correlated with local SSTs but not during all 30-year sub-periods: Egypt, Cebu, Clipperton, Maiana, Galapagos, Malindi, Seychelles, Moorea, Raratonga, Ningaloo, New Caledonia and Houtman Abrolhos.
- Those records which were significantly correlated with local SSTs during all possible 30-year sub-periods: Palmyra, Kiritimati, Tarawa and Nauru. At these four sites the local SST:SOI relationship was also significant and stable through time and there was also a significant and stable coral:SOI relationship.

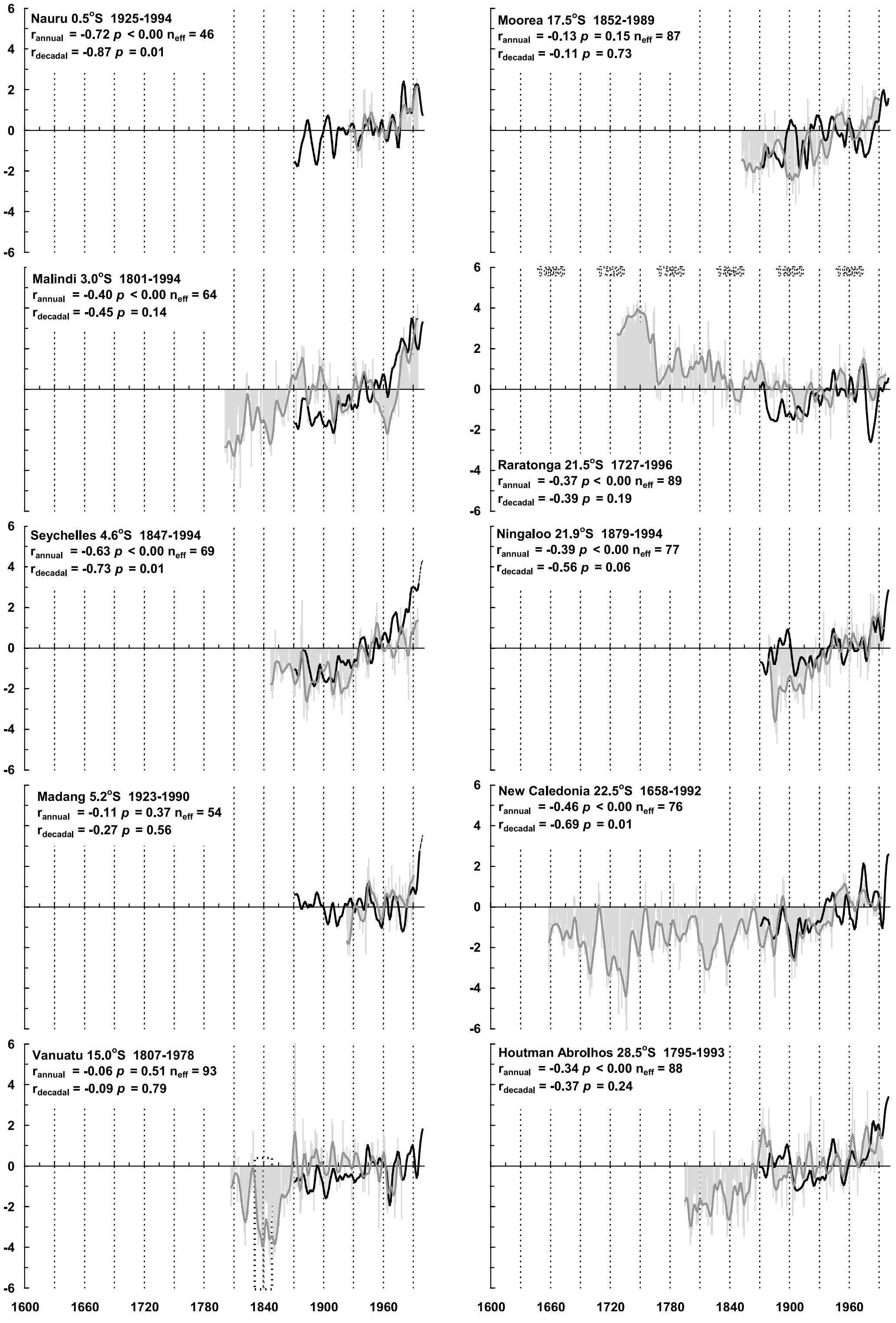
Only one coral record (Nauru) showed a significant and stable relationship with local rainfall as well as SSTs. The two coral records for which $\delta^{18}O$ was suggested to be primarily related to rainfall (Secas and Madang, see Table 1) did not show significant relationships with local rainfall.

3.3. Comparison of coral:SST relationships for maximum, minimum and annual average values

To test for possible seasonal differences in the strength of the coral:climate relationships, separate coral:SST regressions were examined for annual $\delta^{18}O$ maximum with annual minimum SSTs, annual $\delta^{18}O$ minimum with annual maximum SSTs and annual averages of $\delta^{18}O$ and SSTs over the period 1931–1990. This was possible for 16 of the series for which the coral data were provided at sub-annual resolution.

From the resulting regressions (Table 4) the 16


Aqaba 29.4°N 1788-1992
r_{annual} = -0.10 p = 0.32 n_{eff} = 101
$r_{decadal}$ = -0.46 p = 0.13
Palmyra 5.9°N 1886-1997
r_{annual} = -0.72 p < 0.00 n_{eff} = 80
$r_{decadal}$ = -0.66 p = 0.03
Egypt 27.8°N 1751-1995
r_{annual} = -0.30 p < 0.00 n_{eff} = 91
$r_{decadal}$ = -0.30 p = 0.34
Kiritimati 2.0°N 1939-1992
r_{annual} = -0.66 p < 0.00 n_{eff} = 46
$r_{decadal}$ = -0.41 p = 0.49
Cebu 10.5°N 1859-1980
r_{annual} = -0.22 p = 0.02 n_{eff} = 81
$r_{decadal}$ = -0.32 p = 0.34
Maiana 1.0°N 1840-1993
r_{annual} = -0.60 p < 0.00 n_{eff} = 78
$r_{decadal}$ = -0.53 p = 0.08
Clipperton 10.3°N 1894-1993
r_{annual} = -0.46 p < 0.00 n_{eff} = 78
$r_{decadal}$ = -0.59 p = 0.07
Tarawa 1.0°N 1894-1989
r_{annual} = -0.56 p < 0.00 n_{eff} = 73
$r_{decadal}$ = -0.38 p = 0.28
Secas 8.0°N 1708-1983
r_{annual} = -0.22 p = 0.02 n_{eff} = 81
$r_{decadal}$ = -0.43 p = 0.19
Galapagos 0.4°S 1607-1952
r_{annual} = -0.27 p = 0.02 n_{eff} = 80
$r_{decadal}$ = +0.08 p = 0.85
6
4
2
0
-2
-4
-6
1600
1660
1720
1780
1840
1900
1960


Nauru 0.5°S 1925-1994
r_annual = -0.72 p < 0.00 n_eff = 46
r_decadal = -0.87 p = 0.01
Moorea 17.5°S 1852-1989
r_annual = -0.13 p = 0.15 n_eff = 87
r_decadal = -0.11 p = 0.73
Malindi 3.0°S 1801-1994
r_annual = -0.40 p < 0.00 n_eff = 64
r_decadal = -0.45 p = 0.14
Raratonga 21.5°S 1727-1996
r_annual = -0.37 p < 0.00 n_eff = 89
r_decadal = -0.39 p = 0.19
Seychelles 4.6°S 1847-1994
r_annual = -0.63 p < 0.00 n_eff = 69
r_decadal = -0.73 p = 0.01
Ningaloo 21.9°S 1879-1994
r_annual = -0.39 p < 0.00 n_eff = 77
r_decadal = -0.56 p = 0.06
Madang 5.2°S 1923-1990
r_annual = -0.11 p = 0.37 n_eff = 54
r_decadal = -0.27 p = 0.56
New Caledonia 22.5°S 1658-1992
r_annual = -0.46 p < 0.00 n_eff = 76
r_decadal = -0.69 p = 0.01
Vanuatu 15.0°S 1807-1978
r_annual = -0.06 p = 0.51 n_eff = 93
r_decadal = -0.09 p = 0.79
Houtman Abrolhos 28.5°S 1795-1993
r_annual = -0.34 p < 0.00 n_eff = 88
r_decadal = -0.37 p = 0.24
6
4
2
0
-2
-4
-6
1600
1660
1720
1780
1840
1900
1960

coral series could be divided into the following groups:

- Those series which did not show a significant relationship with either maximum, minimum or annual values (Secas and Vanuatu).
- Those series which showed a significant relationship with only maximum SSTs (Moorea and New Caledonia).
- Those series which showed a significant relationship only with minimum SSTs (Egypt) and with minimum and annual values (Clipperton, Seychelles and Madang).
- Those series which showed significant relationships with maximum, minimum and annual values (Palmyra, Kiritimati, Maiana, Tarawa, Nauru, Raratonga, Ningaloo and Houtman Abrolhos). For six of these eight series the slope of the regression was steeper for maximum SSTs and minimum δ^{18}O than for minimum SSTs and maximum δ^{18}O. This suggests that the coral δ^{18}O was capturing summer SST variability better than winter SST variability. This may, in part, be a reflection of seasonal changes in coral growth rates (Barnes et al., 1995) which results in a greater number of geochemical samples from the summer season of faster growth than the winter season of slower growth (Wellington et al., 1996).

3.4. Comparison of coral $\delta^{18}O$ and $\delta^{13}C$ records

The carbon isotopic record in coral skeletons has always been considered to have a less straightforward environmental interpretation than the oxygen isotope record but can easily be measured at the same time and thus is often also reported (Dunbar and Cole, 1999). Both δ^{18}O and δ^{13}C measurements were available for 11 of the coral sites. At nine of the 11 sites there was close agreement between the inter-annual and decadal variations of δ^{18}O and δ^{13}C (Fig. 4). Only two sites, Aqaba and Kiritimati, did not show any relationship between the time series of the two isotopes. Two sites, Aqaba and Clipperton, showed a dramatic drop in δ^{13}C which began in the late 1950s/early 1960s.

3.5. Comparison of coral and observed extremes

For the record period common to the coral and local observed SST records, the five warmest and five coldest years were identified. The five most extreme positive and negative values were then identified in each coral record. The agreement between local SST extreme and coral extreme years was extremely low and only the record from Kiritimati correctly identified more than half of the locally observed extreme SST years (Table 5).

3.6. Comparison of linear trends in coral and SST records

It could be argued that the instrumental record of SSTs is inhomogeneous so that comparisons with coral records, particularly in the early part of the 20th century are not valid (Hurrell and Trenberth, 1999). If we assume that the instrumental SST record is likely to be most reliable in the latter half of the 20th century, then how well are linear trends in SSTs captured in the coral records? To do this the linear trend of the annual average SST record was determined for the period 1951–1990. The annual linear trend over the same period was then determined from the coral record. The coral trend was converted to SSTs (°C) with no allowance for possible salinity effects based on the 0.20‰ per °C for the δ^{18}O series (see review of various calibrations in Evans

Fig. 3. Annual standardized anomalies of coral series (gray bars), 10-year Gaussian filtered coral series (thick gray line; various record lengths) and 10-year Gaussian filtered SSTs (thick black line, 1871–1999). Both coral and SST series standardized with respect to 1931–1960 mean and S.D. Coral series multiplied by −1 so that negative values indicate cooler and/or drier and/or more saline conditions and positive values indicate warmer and/or wetter and/or less saline conditions. Series are arranged latitudinally from the most northerly (Aqaba) to the most southerly (Houtman Abrolhos) sites. The correlation coefficient between annual coral SST series, significance level and number of degrees of freedom adjusted for autocorrelation also given for all overlapping years as well as correlation coefficients for 10-year Gaussian filtered series.

Table 3
Correlations of annual coral series with annual local SSTs (CSST), local rainfall (CRF), the SOI (CSOI) and local SSTs with the SOI (SSTSOI) for 30-year periods

Coral site	1871–1900			1901–1930				1931–1960				1961–1990			
	CSST	CSOI	SSTSOI	CSST	CRF	CSOI	SSTSOI	CSST	CRF	CSOI	SSTSOI	CSST	CRF	CSOI	SSTSOI
Aqaba	−0.28	0.04	−0.01	0.26	−0.28	−0.27	0.25	0.13	−0.17	0.27	−0.09	0.10	0.05	0.30	0.25
Egypt	**−0.42**	0.14	−0.01	**−0.42**	0.25	0.05	0.25	−0.38	0.23	0.18	−0.08	**−0.43**	−0.12	−0.05	0.12
Cebu	−0.02	−0.28	0.00	0.05	−0.23	0.20	0.17	−0.06	0.01	−0.26	−0.19	**−0.58**	−0.21	−0.04	−0.13
Clipperton Atoll			**−0.73**	**−0.68**		**0.37**	**−0.62**	−0.19		0.10	**−0.71**	**−0.45**		**0.53**	**−0.79**
Secas Is	−0.13	−0.05	**−0.60**	−0.18	0.06	−0.09	**−0.55**	−0.11	−0.21	−0.10	**−0.65**	−0.10	−0.33	−0.06	**−0.77**
Palmyra Is			**−0.76**	**−0.66**		**0.54**	**−0.55**	**−0.81**		**0.62**	**−0.77**	**−0.83**		**0.71**	**−0.80**
Kiritimati Is			**−0.78**				**−0.60**	**−0.70**	−0.06	**0.71**	**−0.80**	**−0.60**	**−0.62**	**0.76**	**−0.86**
Maiana Atoll	−0.22	0.34	**−0.72**	**−0.61**		**0.70**	**−0.54**	**−0.65**		**0.68**	**−0.74**	**−0.72**		**0.70**	**−0.81**
Tarawa Atoll			**−0.72**	**−0.61**		**0.71**	**−0.54**	**−0.59**		**0.63**	**−0.74**	**−0.60**		**0.64**	**−0.81**
Galapagos Is	−0.12	0.21	**−0.70**	0.22		**0.38**	**−0.49**	**−0.58**		**0.68**	**−0.67**				**−0.68**
Nauru Is			**−0.65**				**−0.45**	**−0.60**	**−0.77**	**0.69**	**−0.55**	**−0.79**	**−0.65**	**0.69**	**−0.63**
Malindi	−0.08	0.10	**−0.36**	−0.19	−0.07	0.13	−0.35	−0.06	−0.03	0.19	**−0.44**	**−0.71**	0.13	0.31	−0.27
Seychelles	**−0.41**	0.26	**−0.39**	−0.23	−0.30	**0.51**	**−0.42**	**−0.40**	−0.22	0.13	**−0.51**	**−0.39**	−0.03	**0.42**	−0.36
Madang			**0.65**				**0.55**	−0.42	−0.08	−0.08	**0.50**	−0.02	0.02	0.14	**0.63**
Vanuatu	−0.17	−0.11	**0.62**	−0.14		0.06	**0.53**	0.17		0.13	**0.68**				**0.56**
Moorea	0.35	0.03	**−0.53**	0.04		0.29	**−0.46**	−0.30	−0.30	0.17	**−0.51**	**−0.42**	0.07	0.12	**−0.37**
Raratonga	−0.24	−0.27	**0.67**	−0.17		**−0.39**	0.30	−0.30		−0.47	**0.42**	**−0.70**		**−0.64**	**0.63**
Ningaloo	−0.38	−0.24	0.20	−0.23	−0.15	−0.25	0.23	−0.12	−0.22	−0.23	**0.37**	**−0.51**	0.30	−0.03	0.21
New Caledonia	−0.31	−0.23	**0.44**	−0.38	0.04	−0.22	**0.59**	0.11	**−0.47**	−0.10	**0.41**	**−0.50**	−0.20	−0.34	**0.63**
Houtman Abrolhos Is	0.19	−0.31	0.09	**−0.45**	**−0.57**	**−0.38**	0.25	−0.25	−0.33	−0.03	0.07	**−0.41**	−0.04	0.10	0.00

Values in bold are significant at the 5% level after adjusting degrees of freedom for lag 1 autocorrelation.

Table 4
Slope of the regression between annual, maximum and minimum coral δ^{18}O and annual, minimum and maximum SST values over the period 1931–1990 (to 1989 for Tarawa)

Coral site	Annual	Maximum δ^{18}O and minimum SST	Minimum δ^{18}O and maximum SST
Egypt	−0.05	**−0.07**	−0.04
Clipperton Atoll	**−0.12**	**−0.19**	−0.03
Secas Is	−0.05	−0.01	0.01
Palmyra Is	**−0.23**	**−0.14**	**−0.26**
Kiritimati Is	**−0.17**	**−0.11**	**−0.20**
Maiana Atoll	**−0.28**	**−0.17**	**−0.39**
Tarawa Atoll	**−0.22**	**−0.14**	**−0.30**
Nauru Is	**−0.51**	**−0.37**	**−0.43**
Seychelles	**−0.12**	**−0.14**	−0.06
Madang	**−0.30**	**−0.36**	−0.10
Vanuatu	−0.04	−0.05	−0.03
Moorea	−0.11	−0.01	**−0.13**
Raratonga	**−0.07**	**−0.06**	**−0.06**
Ningaloo	**−0.14**	**−0.11**	**−0.11**
New Caledonia	−0.10	−0.04	**−0.09**
Houtman Abrolhos Is	**−0.12**	**−0.07**	**−0.17**

Values in bold are significant at the 5% level after adjusting the degrees of freedom for lag 1 autocorrelation.

et al., 2000; Juillet-Leclerc and Schmidt, 2001) and 0.062 mmol/mol/°C for the Raratonga Sr/Ca record (see review of various calibrations in Gagan et al., 2000). Sixteen of the coral series which covered the period 1951–1990 (to 1989 for Tarawa) were examined.

Average annual SSTs warmed between 1951–1990 at 11 of the 16 sites (Table 6). This warming was significant (at the 5% level) at five of these sites. Over this time period, instrumental SSTs significantly cooled at Raratonga. The coral-based SST estimates indicated warming at 12 of the sites, this warming was significant (at the 5% level) at 11 of these sites. Significant cooling of coral-based SSTs was found for New Caledonia. The 16 series could be divided into the following groups:

- Observed SST cooling correctly identified by coral (Aqaba and Raratonga). At Aqaba, the coral overestimates the cooling and at Raratonga the coral underestimates the cooling.
- Observed SST warming correctly identified by coral (Clipperton, Palmyra, Maiana, Tarawa, Nauru, Malindi, Madang, Ningaloo and Houtman Abrolhos). Two of the coral series, Clipperton and Houtman Abrolhos, slightly underestimate the degree of warming. Three of the coral series slightly overestimate the degree of warming (Madang, Malindi and Ningaloo; 0.1–0.7°C) whilst four of the coral series overestimate the degree of warming by more than 1°C (Palmyra, Maiana, Tarawa and Nauru).
- Observed SST cooling incorrectly identified as warming in the coral record (Egypt, Kiritimati and Moorea).
- Observed SST warming incorrectly identified as cooling in the coral record (Seychelles and New Caledonia).

Over all 16 sites, the average annual warming of SSTs between 1951 and 1990 averaged 0.17 ± 0.36°C (range −0.36 to +0.89°C). Over the same period, the average annual warming estimated from the coral records was +0.73 ± 0.87°C (range −0.65 to +2.44°C). The average difference between the coral estimate and observed SST trend was +0.56 ± 0.88°C (range −0.85 to +2.25°C).

Over all available years for each coral record (and using the above ‘calibrations’) 19 of the coral records suggested warming of SSTs and one, Raratonga, showed cooling (Table 7). The warming trends were significant (at the 5% level) at 16 of the sites with highest values (∼2.2°C) at Maiana and Nauru.

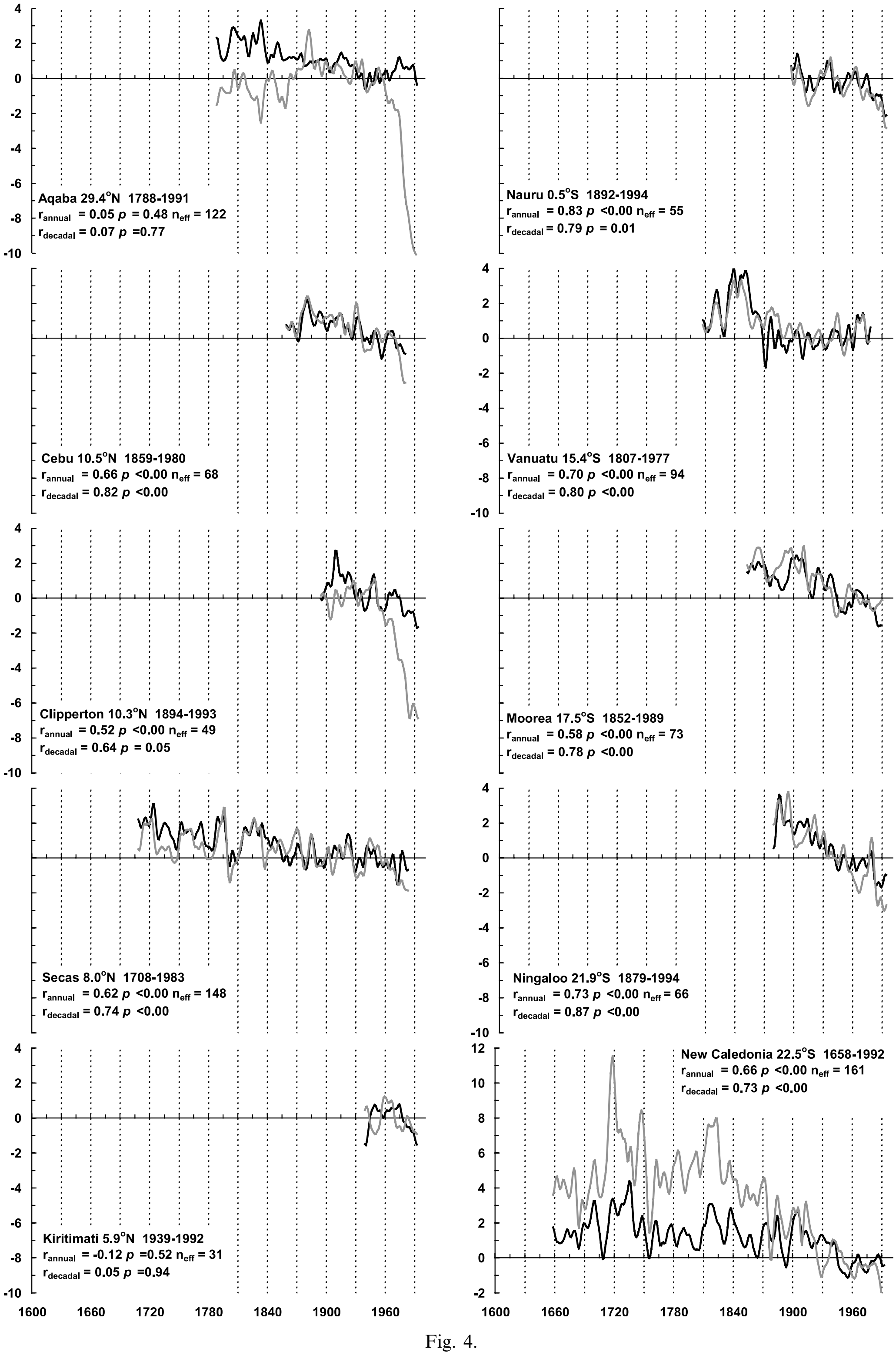

Aqaba 29.4°N 1788-1991
r_{annual} = 0.05 p = 0.48 n_{eff} = 122
$r_{decadal}$ = 0.07 p =0.77
Nauru 0.5°S 1892-1994
r_{annual} = 0.83 p <0.00 n_{eff} = 55
$r_{decadal}$ = 0.79 p = 0.01
Cebu 10.5°N 1859-1980
r_{annual} = 0.66 p <0.00 n_{eff} = 68
$r_{decadal}$ = 0.82 p <0.00
Vanuatu 15.4°S 1807-1977
r_{annual} = 0.70 p <0.00 n_{eff} = 94
$r_{decadal}$ = 0.80 p <0.00
Clipperton 10.3°N 1894-1993
r_{annual} = 0.52 p <0.00 n_{eff} = 49
$r_{decadal}$ = 0.64 p = 0.05
Moorea 17.5°S 1852-1989
r_{annual} = 0.58 p <0.00 n_{eff} = 73
$r_{decadal}$ = 0.78 p <0.00
Secas 8.0°N 1708-1983
r_{annual} = 0.62 p <0.00 n_{eff} = 148
$r_{decadal}$ = 0.74 p <0.00
Ningaloo 21.9°S 1879-1994
r_{annual} = 0.73 p <0.00 n_{eff} = 66
$r_{decadal}$ = 0.87 p <0.00
Kiritimati 5.9°N 1939-1992
r_{annual} = -0.12 p =0.52 n_{eff} = 31
$r_{decadal}$ = 0.05 p =0.94
New Caledonia 22.5°S 1658-1992
r_{annual} = 0.66 p <0.00 n_{eff} = 161
$r_{decadal}$ = 0.73 p <0.00
4
2
0
-2
-4
-6
-8
-10
12
10
8
6
4
2
0
-2
1600
1660
1720
1780
1840
1900
1960

Fig. 4.

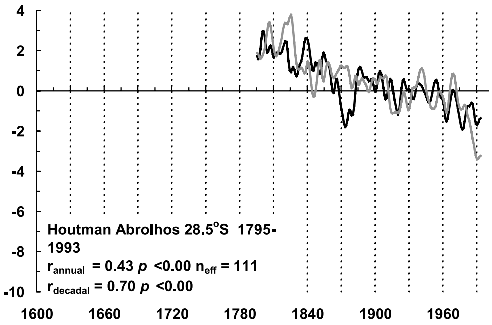


Fig. 4 (*Continued*). 10-Year Gaussian filtered $\delta^{18}O$ (black) and $\delta^{13}C$ (gray). All series are standardized anomalies with respect to mean and S.D. of 1931–1960. Note different scale for New Caledonia. Correlation of annual and 10-year filtered values over common period also given.

3.7. Estimation of SOI from SST and coral records – is the total greater than the sum of the parts?

The SST and coral records from 14 of the 20 sites were examined using PCA to see whether as a group and with reduced subsets they were successful at capturing ENSO variability through time. Annual values of the SOI were estimated using multiple regression from the first two PCs from various analyses. The 14 sites were selected on the basis of being in regions that are influenced by ENSO and instrumental records showing significant relationship with the SOI (see Table 3). Although Galapagos records an ENSO signal, it was excluded from this experiment due to the series ending in 1952. The 14 series range from Clipperton Atoll at ~10°N to New Caledonia ~23°S. The common period (dictated by the latest start year (1939 for Kiritimati) and earliest end year (1978 for Vanuatu)) was 1939–1978.

The first PC for SST14 explained 55% of the total variance and was significantly correlated with the SOI (Table 8). The PC loadings highlighted the out-of-phase relationship of ENSO with sites in the central and eastern Pacific compared with sites in the southern Pacific (e.g. Madang, Vanuatu, Raratonga and New Caledonia). These different relationships with the SOI were also, to a large extent, reflected in the PC loadings of the first Coral14 PC, though this only explained 31% of the variance. When the number of sites was reduced to eight and five, both SST PCs showed significant relationships with the SOI. This was not found when the smaller subsets of the coral series were analyzed. The Coral5 PC2, which was significantly correlated with the SOI, was almost totally dominated by the contribution from the Raratonga coral series.

Table 5
Comparison of SST and isotope extremes

Coral site	Period	Matched extremes (%)
Aqaba	1871–1992	0
Egypt	1871–1995	10
Cebu	1871–1980	0
Clipperton Atoll	1894–1993	30
Secas Is	1871–1983	0
Palmyra Is	1886–1997	50
Kiritimati Is	1939–1992	60
Maiana Atoll	1871–1993	20
Tarawa Atoll	1894–1988	30
Galapagos Is	1871–1952	30
Nauru Is	1925–1994	30
Malindi	1871–1994	10
Seychelles	1871–1994	10
Madang	1923–1990	10
Vanuatu	1871–1978	0
Moorea	1871–1989	10
Raratonga	1871–1996	10
Ningaloo	1879–1994	40
New Caledonia	1871–1992	30
Houtman Abrolhos Is	1871–1993	0

Percentage of 10 most extreme SST years also identified in top 10 most extreme years in annual coral record over indicated time period.

All six multiple regression estimates of the SOI were statistically significant (Table 9). For the SST series, the SOI variance explained declined only slightly between the SST14 and SST8 calibrations (from 85 to 80%) and slightly more to the SST5 calibration (68%). The SST8 and SST5 reconstructions were significantly verified with the SOI over the independent period, 1871–1938. The SST-based reconstructions also showed significant correlations with the Madras annual SLP series over various time periods. The Coral14 reconstruction of the SOI explained 72% of the variance and was also significantly verified. The SST14, Coral14 and observed SOI were closely matched over the calibration period 1938–1978 (Fig. 5a). Reducing the number of coral records resulted in a greater drop in explained variance than found for the SST series; to 54% with eight corals and to 39% with five corals. Both these reconstructions were, however, significantly correlated with the SOI over the independent verification period, 1871–1938 – though the explained variance over the verification period dropped substantially more than found for the reduced SST calibrations to 29% and 10% for the Coral8 and Coral5 series, respectively. Neither of these two reconstructions was significantly correlated with the Madras SLP series prior to 1871, thus reducing confidence in the reliability of the longer-term reconstructions (Fig. 5b,c).

4. Summary

Comparisons of average $\delta^{18}O$ with average SST (from ~21 to 29°C) support a temperature dependence of $\delta^{18}O$ of −0.22‰ per °C, within the range of previously reported studies (Evans et al., 2000; Juillet-Leclerc and Schmidt, 2001). Thus, corals from warmer waters will tend to be more depleted in $\delta^{18}O$ than those from cooler waters though there was considerable spread in the relationship which only explains 46% of average $\delta^{18}O$ variance (Fig. 2a). The mixed nature of the $\delta^{18}O$ signal in corals was, however, evident from analyses of $\delta^{18}O$, average SST (from ~24 to 29°C) and average salinity (from ~33 to 36‰) at 12 Pacific sites. About 30% of the variance in average coral $\delta^{18}O$ was explained by SST variations whilst 60% of the variance was explained by sa-

Table 6
Linear trend analysis of annual SSTs and annual coral records for 16 sites over the period 1951–1990 (to 1989 for Tarawa)

Coral site	Instrumental SST			Coral record		
	R^2	p	SST change (°C)	R^2	p	Coral estimate of SST change (°C)
Aqaba	0.02	0.39	−0.19	0.09	0.06	−0.65
Egypt	0.02	0.35	−0.21	**0.13**	**0.02**	**+0.51**
Clipperton Atoll	0.07	0.09	+0.23	0.02	0.34	+0.19
Palmyra Is	0.00	0.86	+0.05	**0.24**	**<0.00**	**+1.24**
Kiritimati Is	0.02	0.27	−0.34	**0.17**	**<0.00**	**+1.10**
Maiana Atoll	0.01	0.48	+0.19	**0.46**	**<0.00**	**+2.44**
Tarawa Atoll	0.00	0.77	+0.08	**0.31**	**<0.00**	**+1.62**
Nauru Is	0.08	0.08	+0.38	**0.24**	**<0.00**	**+1.92**
Malindi	**0.38**	**<0.00**	**+0.58**	**0.56**	**<0.00**	**+1.40**
Seychelles	**0.23**	**<0.00**	**+0.41**	0.01	0.61	−0.11
Madang	0.06	0.14	+0.23	**0.10**	**0.05**	**+0.78**
Moorea	0.00	0.88	−0.02	**0.11**	**0.04**	**+0.66**
Raratonga	**0.11**	**0.04**	**−0.36**	0.01	0.57	−0.21
Ningaloo	**0.22**	**<0.00**	**+0.51**	**0.12**	**0.03**	**+0.66**
New Caledonia	**0.13**	**0.02**	**+0.33**	**0.11**	**0.03**	**−0.52**
Houtman Abrolhos Is	**0.43**	**<0.00**	**+0.89**	**0.13**	**0.02**	**+0.66**
Average °C			+0.17			+0.73

Total estimated change in coral SSTs based on 0.20‰/°C for $\delta^{18}O$ series and 0.062 mmol/mol/°C for the Raratonga Sr/Ca record. Values in bold are significant at the 5% level.

linity variations. Average SST and salinity at these sites were not significantly correlated and a multiple regression of SST and salinity explained 74% of the variance in coral δ^{18}O. Thus, corals from warmer and/or fresher ocean waters will be more depleted in δ^{18}O, though the primary control on mean δ^{18}O appears to be salinity. The relationship between salinity and coral δ^{18}O was, however, different when inter-annual variations were compared at 10 Pacific sites. Only one coral δ^{18}O series, Nauru, showed a significant combined signal of both temperature and salinity after allowing for the covariation of the latter two variables and no coral record exhibited only a salinity signal. It is clear from this brief analysis and more detailed studies (Morimoto et al., 2002; Ren et al., 2002) that there is still much to learn about the varying control of δ^{18}O by SST and salinity and, therefore, what exactly long-term records of δ^{18}O are recording. Improved understanding of the controls of coral δ^{18}O variations in space and through time will be facilitated by high-quality instrumental observations of salinity at coral reef sites.

Over all available overlapping years, the majority of the coral series showed significant relationships with inter-annual variations of local SSTs. Only four of the coral series, however, showed significant agreement with decadal variations of SSTs. This suggests that existing coral records may not be successfully capturing decadal climate variability. This creates problems for interpreting apparent decadal variations in the pre-instrumental record period.

Only four coral series showed significant relationships with climate variables that were stable over time. Eleven of the coral series showed significant relationships but these were not stable through time. At eleven sites, the relationship between instrumental SST and the SOI was significant and stable through time. The variability in the strength of the relationships between some

Table 7
Linear trend analysis of annual coral records for 20 sites over total record periods shown

Coral site	Period	R^2	p	Estimated SST change (°C)
Aqaba	1788–1992	**0.30**	**< 0.00**	**+1.57**
Egypt	1751–1995	**0.40**	**< 0.00**	**+1.43**
Cebu	1859–1980	**0.24**	**< 0.00**	**+1.92**
Clipperton Atoll	1894–1993	**0.28**	**< 0.00**	**+0.87**
Secas Is	1707–1984	**0.32**	**< 0.00**	**+1.82**
Palmyra Is	1886–1997	**0.34**	**< 0.00**	**+1.78**
Kiritimati Is	1938–1994	0.03	0.18	+0.64
Maiana Atoll	1840–1993	**0.36**	**< 0.00**	**+2.25**
Tarawa Atoll	1894–1989	0.02	0.20	+0.38
Galapagos Is	1607–1952	0.00	0.80	+0.05
Nauru Is	1925–1994	**0.24**	**< 0.00**	**+2.48**
Malindi	1801–1994	**0.28**	**< 0.00**	**+1.00**
Seychelles	1847–1994	**0.28**	**< 0.00**	**+0.90**
Madang	1923–1990	**0.19**	**< 0.00**	**+1.22**
Vanuatu	1807–1978	**0.14**	**< 0.00**	**+1.27**
Moorea	1852–1989	**0.39**	**< 0.00**	**+1.71**
Raratonga	1727–1996	**0.36**	**< 0.00**	**−2.18**
Ningaloo	1879–1994	**0.50**	**< 0.00**	**+1.82**
New Caledonia	1658–1992	**0.19**	**< 0.00**	**+1.44**
Houtman Abrolhos Is	1795–1993	**0.35**	**< 0.00**	**+1.33**
Average °C				+1.22

Total estimated change in coral SSTs based on 0.20‰/°C for δ^{18}O series and 0.062 mmol/mol/°C for the Raratonga Sr/Ca record. Values in bold are significant at the 5% level.

Table 8
Loadings on first two PCs for 14, eight and five site instrumental and coral PCAs

Coral site	SST14		SST8		SST5		Coral14		Coral8		Coral5	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
New Caledonia	*−0.50*	*−0.58*	−0.13	*−0.88*	*−0.89*	0.09	*−0.57*	*−0.50*	***0.64***	−0.44	*−0.68*	−0.33
Secas	***0.81***	−0.13	***0.88***	−0.10	0.05	***0.90***	−0.28	−0.17	0.37	−0.44	*−0.69*	−0.17
Raratonga	*−0.57*	*−0.54*	−0.17	*−0.78*	*−0.81*	−0.08	*−0.66*	−0.40	0.23	*−0.60*	0.09	*−0.88*
Malindi	0.47	−0.48	***0.76***	−0.45	−0.27	***0.88***	0.35	−0.28	0.07	0.34	*−0.59*	0.29
Vanuatu	*−0.70*	−0.49	−0.35	*−0.81*	*−0.89*	−0.24	−0.10	−0.44	−0.14	0.12	*−0.60*	0.15
Maiana	***0.95***	−0.03	***0.85***	0.34			***0.66***	−0.48	***0.65***	***0.59***		
Seychelles	0.46	*−0.65*	***0.76***	−0.45			0.34	*−0.68*	***0.77***	0.28		
Moorea	***0.52***	*−0.54*	***0.68***	−0.05			−0.01	*−0.75*	***0.71***	−0.03		
Palmyra	***0.91***	0.09					***0.77***	0.21				
Clipperton	***0.83***	−0.28					0.45	−0.28				
Tarawa	***0.95***	−0.03					***0.78***	0.00				
Nauru	***0.77***	−0.24					***0.79***	−0.16				
Madang	*−0.66*	−0.40					−0.36	0.18				
Kiritimati	***0.93***	0.12					***0.82***	0.19				
% Variance	54.5	15.3	41.2	32.2	46.3	33.2	31.1	15.6	26.8	16.4	33.2	20.4
R vs. SOI	**−0.92**	−0.06	**−0.82**	**−0.58**	**−0.66**	**−0.72**	**0.85**	−0.07	0.17	**0.71**	0.09	**0.61**

Component loadings < −0.5 are italic and > +0.5 bold and italic to highlight sites contributing most to each component. The percentage of total variance explained by each component is also given as well as the correlation coefficient between the component time series and the SOI over the period 1939–1978 (bold indicates significance at 5% level).

coral records and local climate suggests that non-climatic factors may be affecting the fidelity of the coral:climate relationship over time.

It is possible that corals may capture different parts of the annual cycle with different fidelity and that this may be lost in examining only annual average values. In particular, due to faster coral growth in summer in some regions, equally spaced sample measurements may over-represent warm season conditions and under-represent cooler season conditions (Wellington et al., 1996). Analyses (Table 4) did show that some corals were capturing different parts of the annual cycle with different levels of significance. Some corals showed significant relationships with both maximum and minimum values. There was, however, no clear pattern amongst corals which did or did not show significant relationships with different parts of the annual cycle. The results suggest, however, that when identifying the climate re-

Table 9
Summary of calibration and verification statistics for six multiple regression estimates of the SOI

Predictors	R^2 SOI Calibration 1939–1978	r SOI Verification 1871–1938	r Madras			
			1939–1978	1871–1938	1852–1870	1807–1851
SST14	84.9%		**−0.68**			
SST8	80.4%	**0.70**	**−0.60**	**−0.67**		
SST5	68.2%	**0.68**	**−0.53**	**−0.64**		
Coral14	72.3%		**−0.60**			
Coral8	54.0%	**0.54**	**−0.60**	**−0.66**	−0.34	
Coral5	39.1%	**0.31**	**−0.53**	**−0.31**	−0.40	−0.17

Correlation coefficients are also provided for various time periods between the coral SOI estimates and the Madras annual SLP series (Allan et al., 2002); the correlation between annual SOI and Madras over the period 1939–1978 was −0.73. Correlation coefficients significant at the 5% level are bold.

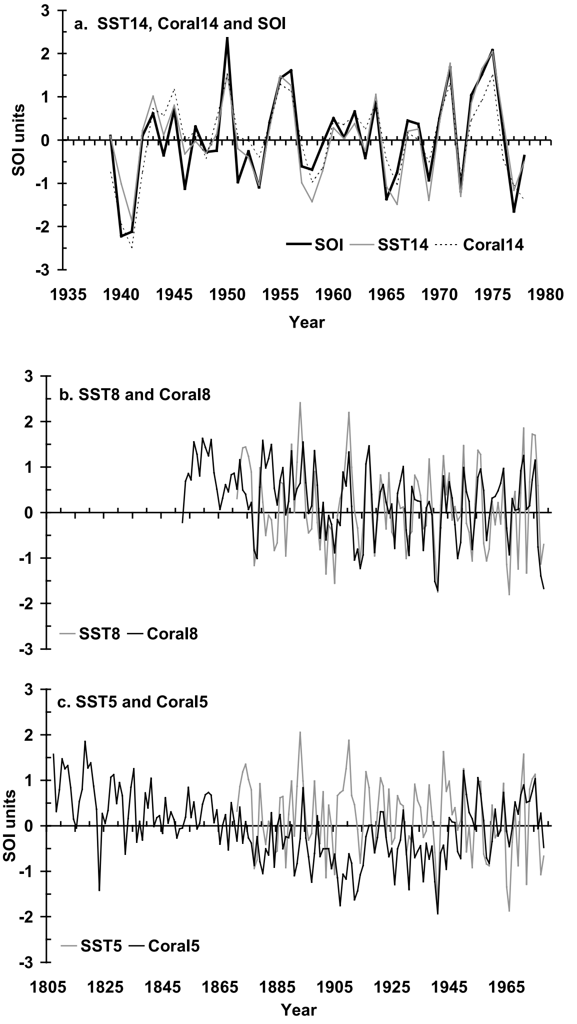


Fig. 5. Reconstructed SOI estimates from (a) SST14 and Coral14, 1939–1978, (b) SST8 1871–1978, Coral8 1852–1978, and (c) SST5 1871–1978 and Coral5 1807–1978.

sponse of a particular coral series that it is informative to consider different parts of the annual cycle separately.

Stable carbon isotope ($\delta^{13}C$) variations in coral skeletons are regarded as being more complicated to interpret than $\delta^{18}O$ or Sr/Ca (see recent review by Grottoli, 2000). Environmental processes, such as light levels and nutrient status, that influence coral metabolism are considered to be the primary sources of variation in coral $\delta^{13}C$. The strong similarity found between annual and decadal variations in coral $\delta^{13}C$ and $\delta^{18}O$ in several coral records (Fig. 4) suggests that either the environmental variables that influence $\delta^{13}C$ and $\delta^{18}O$ are varying in concert or that coral growth processes are similarly affecting the levels of these two variables incorporated into the coral skeleton. Again, more research into the inter-relationships between these geochemical tracers and environmental variables is required to fully understand what each is recording.

The coral records were not very successful at correctly capturing observed climatic extremes. This has implications for interpreting the occurrence and frequency of ‘anomalies’ in coral records, especially relating to ENSO events. The ability to successfully capture climatic extremes may be linked to coral sampling resolution (Quinn et al., 1996b; Watanabe et al., 2002). Records sampled annually averaged 10% matching of coral and climate extremes, whilst coral records based on 10–12 samples per year averaged 27% matching of coral and climate extremes.

Examination of the linear trends obtained from the coral records and observed instrumental SSTs indicate that, if interpreted solely as temperature records, the coral estimates provide an inflated estimate of tropical ocean warming. This has important implications when such records are included in multi-proxy reconstructions of past temperature variations.

It was possible to develop significantly calibrated and verified reconstructions of the SOI from reduced subsets of coral records. The practical significance of these reconstructions may not, however, match their statistical significance (Lough, 1992). The SOI variance explained by instrumental SSTs dropped from 85% to 68% using 14 and five site predictors, respectively. For corals, the explained variance dropped more dramatically from 72% to 39%. In addition, the reconstructions derived from the reduced coral subsets were not significantly correlated with an independent observational record of ENSO variability (Madras SLP, Allan et al., 2002) prior to the mid-19th century. Thus, caution should be exercised in interpreting reconstructions of ENSO variability derived from extant coral records.

5. Discussion and conclusions

Possible climatic interpretations of 20 published coral records have been assessed using a variety of simple statistical analyses. The different analyses provided each coral record with an opportunity to demonstrate a clear and reliable climatic interpretation using consistent techniques amongst the different coral records. It is clear that the published records contain a wide spectrum of climatic interpretations. This spectrum ranges from no significant relationship of the coral record with either local or larger-scale climate variables to significant and temporally stable relationships of the coral record with local and larger-scale climate variables. It is not the purpose of the present paper to present a 'league table' of these published records. It is, however, clear that some coral records may not have any climatic significance at all. No instance was found of a coral record having larger-scale climatic significance but no local-scale climatic significance. Even for those records which show significant relationships with climatic variables, the interpretation of the coral record is not always straightforward (e.g. poor ability of corals to capture most extreme events observed in the instrumental record; overestimating of long-term SST changes). It is also unfortunate that those records which appear to show the most robust relationship with climate also have the shortest record lengths. Rather than discuss the results in detail, here I consider what these results mean for coral-based paleoclimatology and make some recommendations for future work.

The need to understand the nature and causes of past climate variation (especially on inter-annual, decadal and longer time scales) has placed pressure on high-resolution paleoclimatologists to produce records for the past 200–1000-year time period. This pressure has impacted research in two ways. First, from a funding perspective, studies promising climate reconstructions are more likely to be supported than process studies or studies into the reliability of a particular proxy. But for many of the newer climate proxies, process and reliability studies are at least as important as the generation of time series for interpretation of the record. The established science of dendroclimatology is, however, based on almost a century of developing understanding of the mechanisms whereby tree-ring width and density variations record their environment. Second, any published record is rapidly seized upon often regardless of demonstrations (or lack of them) of the reliability and climatic interpretation of the proxy. The accuracy and resolution with which various geochemical tracers can be measured in coral skeletons has outstripped our understanding of the processes by which environmental conditions mediate the incorporation of these materials into the skeleton. Sophisticated statistical analyses cannot make up for limited or no climatic significance of the original coral record. This currently limits the environmental significance, reliability and paleoclimatic application of these records.

It cannot be stressed enough that there are no perfect proxy climate records. It cannot be assumed from theoretical grounds that measurements of particular geochemical tracers in coral skeletons must have a given climatic interpretation. Statistical calibration against instrumental records provides an indication of the climatic interpretation of the record and verification ensures that this model is reliable and stable. In addition, although calibration against absolute values is important for interpreting records from corals from the distant past this may not be so important for modern corals where calibration against relative variations in the instrumental record is just as useful. Calibration and verification statistics for the climate:proxy relationship are standard procedures in dendroclimatic reconstructions which are routinely reported. Some typical values of explained variance from recently published dendroclimatic reconstructions report calibrated variances between 21–63% and 23–68% variance verified over independent time periods (Biondi et al., 2001; Pederson et al., 2001; Cook et al., 2002; Oberhuber and Kofler, 2002). Similar ranges are possible with corals even at much smaller levels of replication and over broad spatial scales. For example, if we take 1961–90 as the 'calibration' period and 1931–60 as the 'verification' period, calibrated variance in the five coral records showing significant and stable climate linkages (Table 3;

Palmyra, Kiritimati, Mainana, Tarawa and Nauru) ranges from 35 to 69% with 36–66% variance verified.

Lack of or poor statistical calibrations of the coral and climatic record may be due to errors in age assignments along the length of the coral and by growth and/or other processes (e.g. early marine diagenesis) compromising parts or all of the coral record and introducing non-climatic variability, thus reducing the climatic sensitivity of the coral record (Allison et al., 1996; Guzman and Tudhope, 1998; Grottoli, 1999, 2002; Guilderson and Schrag, 1999; Al-Rousan et al., 2002; Muller et al., 2002). Replication is the key to identifying and allowing for these potential sources of error in coral paleoclimatology. Although the combined climatic signal from more than one coral may not be larger than that from a single core (e.g. Nauru 1 and Nauru 2), the enhanced reliability clearly improves the interpretation (Hendy et al., 2003). With only two records from a particular site it will not, however, be possible to know which of the two records is correct when they disagree. Ideally, therefore, at least three independent records from the same location need to be analyzed. It is impossible in developing proxy climate records from corals to achieve the level of replication that is routinely possible in dendroclimatology. Large, centuries-old coral colonies are rare and it is uncommon to find more than a handful on a particular reef. Given this limitation, replication of the records in three separate coral colonies is ideal. Failing that, records can be replicated using different cores from the same colony, different slices from the same core or even different tracks along the same coral slice. Any replication of the record can only improve the level of confidence in the proxy climate signal.

Some conclusions and recommendations from this study are:

- Reliable and consistent interpretation of geochemical records from corals as climate proxies is the key issue rather than the precision with which such records can now be measured.
- The strength of the coral:climate relationship varies amongst different corals and, in some corals, over time.
- We may have to accept that some coral records contain little or no information about climate variability.
- Identifying non-climatic artifacts in individual coral records and along the length of a coral record can be achieved through replication. Replication not only ensures dating accuracy but also that a common environmental signal is present.
- Climate reconstructions from corals (and other sources) that extend into the pre-instrumental period should be verified with proxy climate reconstructions based on independent data sets.
- More detailed process studies of how corals record environmental conditions are required to better understand how to interpret the records that can now be precisely measured. For example, analyses of geochemical tracers from multiple samples (e.g. short cores or small colonies) across known environmental gradients in target reef areas would help establish the reproducibility of the paleoclimatic signal as well as environmental factors (e.g. oceanic exposure, turbidity, depth) and coral growth processes that might modify the recording of this signal.
- High quality instrumental observations of a range of climate variables (e.g. SST, salinity, light) in coral reef areas are crucial for reliable interpretation and calibration of geochemical tracers in corals.
- It would be useful if the coral paleo-records community could agree on a set of standard statistical procedures that are routinely reported with published reconstructions. This would allow ready intercomparison between different records. For example, it should be standard procedure to verify calibration models with independent data.
- Careful reconnaissance of potential sites is required to ensure that several, large-sized coral colonies are present that are suitable for coring and will provide records of similar length. Sites with only a single large coral colony (however promising looking) should be avoided.
- There is a need to establish a global database of the locations of large, massive coral colonies. Such an internationally accessible database would provide a major resource for coral paleoclimatologists, prevent expensive duplication of coral reconnaissance and collection trips, and identify for national/international protection (e.g. within Ma-

rine Protected Areas) the 'Methusalahs' of the world's coral reefs. This becomes increasingly important as local and global anthropogenic activities threaten the world's coral reef ecosystems.

Acknowledgements

I would like to thank Mike Evans for his extremely helpful and thoughtful comments on the original and revised versions of this paper. Thanks also to Julie Cole for providing the unstandardized Tarawa data.

Appendix. Description of coral records

A.1. Aqaba

Porites spp. from fore-reef at Aqaba, Jordan, northwest Red Sea. Annual stable isotope values based on analysis of each year of growth determined from distance between each low-density band edge in X-radiograph. $\delta^{18}O$ signal interpreted as largely SST. A long-term trend towards lighter values of ~0.4‰ would equal a warming of ~2°C since 1800 and 1.7°C since 1905 in the Gulf of Aqaba. Influence of salinity and freshwater as a source of isotopic variations considered to be minimal. No 'local' calibration of isotopic records with instrumental SSTs but 9-year running mean reported to be significantly correlated ($r = -0.42$, $P < 0.000$) with 9-year running mean of Southern Hemisphere SSTs, ~1870–1992. Both $\delta^{18}O$ and $\delta^{13}C$ records, 1788–1992, included in Mann et al. (1998) Multi-proxy Data Network.

A.2. Egypt

Porites spp. from narrow fringing reef at Ras Umm Sidd, southern tip of Sinai Peninsula, Egypt. Six or more samples analyzed for each year of growth identified from X-radiograph. Within year chronology established by assigning maximum $\delta^{18}O$ of each year to mid-February when SSTs coldest. Assumed constant growth rate and linearly interpolated between successive Februarys. Values interpolated to six equally spaced values per year. Local calibration of seasonal $\delta^{18}O$ with seasonal GISST2.3b SSTs, 1871–1994, gave significant correlation (including annual cycle) of −0.81. Correlation of annual values was −0.41. Authors suggest that SST is primary control of $\delta^{18}O$ on intra-annual time scales but that salinity of seawater is more important inter-annually. Suggest that $\delta^{18}O$ signal 'probably indicates more a mean state of Middle East climate rather than precisely a specific environmental parameter'. Also report significant coherence of $\delta^{18}O$ with NAO, ENSO and all-India rainfall.

A.3. Philippines

Porites lobata from Cebu Island. Annual values of $\delta^{18}O$ and $\delta^{13}C$, 1859–1980. Primary interpretation is temperature.

A.4. Clipperton Atoll

Cores from three colonies of *Porites lobata*. Ten samples measured per year but due to indistinct annual density banding chronology established from annual variations of $\delta^{18}O$ and $\delta^{13}C$. From 1970–1994 lowest $\delta^{18}O$ assigned to month of highest SST and highest $\delta^{18}O$ to month of lowest SST, based on available instrumental record (i.e. fine-tuned). Prior to 1970, lowest $\delta^{18}O$ assigned to average month of maximum SST, May and highest $\delta^{18}O$ to average month of minimum SST, January. All other age assignments based on linear interpolation between these two annual anchor points. Twelve $\delta^{18}O$ values linearly interpolated for each year. Authors report 'similar secular and decadal trends' (but do not provide any statistical quantification) between the long, 101-year $\delta^{18}O$ record and two shorter (49 and 57 year) $\delta^{18}O$ series. Singular spectrum analysis (SSA) identified coherent variability of $\delta^{18}O$ series with ENSO and SST indices and also reports evidence of reduced ENSO variability from 1925 to mid-1940s. Long-term secular trend in $\delta^{18}O$ record parallels SST trends but is nearly twice as large as expected if $\delta^{18}O$ responding primarily to SSTs. Authors suggest maybe a long-term change in salinity associated with rising SSTs.

A.5. Secas Island

Porites lobata at Secas Island, Gulf of Chiriqui. $\delta^{18}O$ analyzed at between 7 and 17 samples per year. Annual chronology established from annual cycle of $\delta^{18}O$ and annual density banding in X-radiographs. Lowest $\delta^{18}O$ each year assigned to November when salinities are lowest. Data linearly interpolated to 10 values per year. Strong annual cycle of $\delta^{18}O$ in coral considered to be primarily driven by seasonal changes in rainfall and $\delta^{18}O_{ppt}$ that induces changes in $\delta^{18}O_{seawater}$ rather than by relatively small annual SST variations. Seasonal variation of rainfall in region largely controlled by seasonal movements of ITCZ. Significant correlation reported between annual maxima and minima of coral $\delta^{18}O$ and the $\delta^{18}O$ of precipitation measured at Howard Air Force Base over the period 1968–1982 ($r = 0.89$) and Panama rainfall ($r = 0.83$). Both these relationships include annual cycle. Authors note (but do not give values) lower correlations when 3-month averages or raw data were used. They also suggest that some of the discrepancy may arise because the 'coral $\delta^{18}O$ is representative of a larger area' than the $\delta^{18}O_{ppt}$ and rainfall records from single stations. They state that 'large seasonal salinity and $\delta^{18}O_{ppt}$ fluctuations in the Gulf of Chiriqui due to ITCZ-related precipitation and runoff account for ~80% of the annual variability in the $\delta^{18}O$. Irregular annual SST variations explain the other 20% of the variance'. (i.e. 100% of variance explained in a proxy!). Authors note that some El Niño events recorded by coral $\delta^{18}O$ and that long-term trend of 0.4‰ is evident and decadal variations in the $\delta^{18}O$ are not related to SSTs but to variations in $\delta^{18}O_{seawater}$ which are directly related to ITCZ rainfall. Both the $\delta^{18}O$ and $\delta^{13}C$ records, 1707–1984, included in Mann et al. (1998) Multi-proxy Data Network.

A.6. Palmyra Island

Porites lutea off western coast of island. $\delta^{18}O$ measured with high sampling frequency and chronology established from annual $\delta^{18}O$ cycle, as annual density bands were ill defined. A monthly time series was produced. Significant correlation ($r = 0.62$) reported between monthly $\delta^{18}O$ and the Niño 3.4 SST index (over an unspecified time period and including the annual cycle). An overall decrease in $\delta^{18}O$ over the 112-year record period would, if solely temperature, equate to a warming of 1.5°C. Authors suggest that about half the $\delta^{18}O$ change probably due to increased precipitation over past century, i.e. change from colder/drier to warmer/wetter conditions. A strong decadal signal is noted in $\delta^{18}O$ record as well as significant coherence with Seychelles coral record and northeast Brazil rainfall.

A.7. Kiritimati Island

Porites spp. from 9 m depth sampled at 25–35 measurements per year. Annual cycle of $\delta^{13}C$ used to develop chronology and produce final series of 12 values per year. Monthly $\delta^{18}O$ anomalies significantly correlated with monthly SST anomalies for Kiritimati Island region ($r = -0.84$, 1981–1987). Annual (April to March) average $\delta^{18}O$ values significantly correlated with annual Niño 3 SST index ($r = -0.79$, 1938–1993). Authors suggest that $\delta^{18}O$ anomaly 'synthesizes a convective atmospheric (enhanced rainfall during ENSO events) as well as a thermal oceanographic signal. Hence the coral $\delta^{18}O$ may make a better climate monitor than either SST of seawater $\delta^{18}O$ anomaly alone'.

A.8. Maiana Atoll

Porites spp. sampled continuously in 1-mm steps. Chronology established from annual cycle of $\delta^{13}C$ and annual density bands in X-radiographs. Series was also 'tuned' to major El Niño and La Niña events. Series interpolated to six values per year. Bimonthly values significantly correlated with three other nearby coral series (*r* values from 0.67 to 0.78 (with annual cycle?)) and with a multivariate ENSO index ($r = -0.76$), Niño 3.4 ($r = -0.58$), central Pacific rainfall ($r = -0.68$), Darwin pressure ($r = -0.50$), Tahiti pressure ($r = 0.40$) and with the SOI ($r = 0.53$). $\delta^{18}O$ series shows long-term trend, mainly since 1976, which if interpreted as temperature would equate to a warming of ~2.0–3.1°C or if purely salinity then a freshening of 2‰. Authors suggest more likely a combined signal from colder/drier to warmer/wetter conditions.

A.9. Tarawa Atoll

Two cores from a *Porites* spp. coral measured at ~16 samples per year. Seasonal cycle of $\delta^{13}C$ and annual density banding pattern used to develop chronology. Two records combined to produce a single time series interpolated to monthly values. Annual values significantly correlated with Darwin pressure ($r = 0.71$), Tahiti pressure ($r = 0.49$), Wright's SOI ($r = 0.72$), Wright's rainfall-based SOI ($r = 0.80$) and Tarawa rainfall ($r = -0.50$). Authors interpret series as largely rainfall-induced changes in salinity and highlight period ~1930–1950 as one of reduced ENSO variability.

A.10. Galapagos Islands

Uplifted colony of *Pavona clavus* sampled for $\delta^{18}O$ in annual increments determined from base of each high-density band observed on X-radiographs. Climatic interpretation based on sub-annual analyses of *P. gagantea* coral, 1961–1983, which was significantly correlated with local monthly SSTs ($r = -0.90$, including annual cycle). Authors report correlation of similar magnitude with annual average SSTs over 15-year period. Significant correlations reported between annual average $\delta^{18}O$ and regional SSTs ($r = -0.88$), Wright's SST index ($r = -0.74$), Wright's rainfall index ($r = -0.64$) but no significant correlation with Wright's SOI ($r = -0.47$), 1965–1982. On the basis of these analyses of the younger, short coral record, authors suggest that annual $\delta^{18}O$ can be used to reconstruct eastern Pacific SSTs and identify past ENSO events. A significant correlation ($r = -0.66$) reported between annual $\delta^{18}O$ values in the longer core and Puerto Chicama SSTs, 1936–1953. The $\delta^{18}O$ record, 1607–1953, included in Mann et al. (1998) Multi-proxy Data Network.

A.11. Nauru Island

Two large colonies of *Porites* spp. less than 20 m apart. Annual density banding unclear in either coral and $\delta^{18}O$ and $\delta^{13}C$ sampled continuously along cores and chronology established from annual $\delta^{13}C$ cycle. Age models refined by 'tuning' against observed rainfall and between two coral cores and four values produced per year. Authors report that despite differences in absolute $\delta^{18}O$ values between two corals that 'the records are coherent and in phase'. Both corals show trend towards warmer and/or fresher waters. A decrease in $\delta^{18}O$ between 1952 and 1995 would equate to a 2.5°C warming or a 2‰ decrease in salinity. Instrumental SSTs in region suggest a warming of only 0.6°C. There also appears to be a marked shift in $\delta^{18}O$ about 1976. Authors report similarity between $\delta^{18}O$ record and Northern Hemisphere and global temperature variations and conclude that Nauru corals are 'a robust recorder of environmental variables' – though no correlations are given and 'accurate, albeit not a precise recorder of temperature or salinity changes'.

A.12. Malindi

Porites lutea with chronology established from clear annual density banding and luminescent lines. $\delta^{18}O$ measured in annual increments determined from top of each low-density band. Authors report significant correlation between annual $\delta^{18}O$ and (November–October) annual instrumental SSTs ($r = -0.69$) and interpret $\delta^{18}O$ as primarily a temperature signal. They show a trend towards lower $\delta^{18}O$ values which if interpreted as purely temperature would indicate a warming of ~1.3°C since 1801 with much of the warming in the late 20th century following a shift in 1976. Significant coherence reported with Niño 3.4 ENSO index and Seychelles coral record and weaker coherence with all-India rainfall and East African rainfall.

A.13. Seychelles

Porites lutea at Mahe Island. $\delta^{18}O$ measured at 1-mm intervals and chronology established from annual $\delta^{18}O$ cycle and annual density banding pattern from X-radiographs. Highest $\delta^{18}O$ value each year assigned to August 1 (average time of coldest SST) and linear interpolation between these annual anchor points used to generate monthly time series. $\delta^{18}O$ record considered to be a 'relatively simple proxy for SST'. Over 15-year period report a significant correlation between monthly $\delta^{18}O$ anomalies and SST anomalies of 0.72. Similarity of the coral record with an index of the Asian summer monsoon intensity also noted but not quantified. A long-term decrease in $\delta^{18}O$ would, if purely temperature, equate to a warming of 0.8°C which is larger than that observed in instrumental SST record. Authors note coherence with ENSO indices in 3–6-year frequency band and marked decadal variability in $\delta^{18}O$ record which does not appear to be simply related to decadal variability in the Pacific but is suggested to be more closely linked to decadal variations in the Indian monsoon system.

A.14. Madang

Porites spp. measured at four samples per year with annual increments determined from annual fluorescent banding pattern and confirmed with $\delta^{18}O$ measurements. $\delta^{18}O$ considered to primarily relate to rainfall and authors report a good visual match between $\delta^{18}O$ record and Madang rainfall since 1950 and a poorer match in the 1920s and 1930s. Similar visual matching also reported between $\delta^{18}O$ and the Tahiti–Darwin SOI. Authors report significant correlations between this and three other coral isotopic records over a 10-year period based on annual running mean values. Based on moving 30-year correlations they report that the strength of the relationship with ENSO decreased prior to 1950 and that this represents a decoupling of the PNG from ENSO in this earlier time period of generally weaker global ENSO teleconnections. A decrease of $\delta^{18}O$ through time would, if purely temperature, equate to a 0.5–1.0°C warming compared with observed SST rise of ~0.4°C.

A.15. Vanuatu

Platygyra lamellina measured at four samples per year. Authors suggest that $\delta^{18}O$ record is likely to contain both a temperature and rainfall component and this reflects either warmer/wetter or cooler/drier conditions. They report correlations of the $\delta^{18}O$ record with instrumental SSTs and rainfall of 0.71 and 0.45, respectively, over a 13-year period. It is unclear as to whether the annual cycle was removed prior to these analyses. The $\delta^{18}O$ record, 1806–1978, included in Mann et al. (1998) Multi-proxy Data Network.

A.16. Moorea

Porites lutea sampled at 2-mm intervals with an average of six samples per year. Due to unclear annual density banding, chronology established from intra-annual variation of $\delta^{18}O$. Annual $\delta^{18}O$ maximum tied to August, the month of average minimum SST and $\delta^{18}O$ minimum to March, the month of average maximum SST. The resulting series contains ~4–8 measurements per year. Authors report various significant correlations between intra- and inter-annual $\delta^{18}O$ and local SSTs with a correlation of 0.76 between annual $\delta^{18}O$ and local SST, 1958–1990. Authors estimate past occurrences of ENSO events from 'signal' of high $\delta^{13}C$ followed by low $\delta^{18}O$ and identify 36 ENSO events affecting Moorea over past 137 years. They conclude that 'although Moorea is not located in a region where ENSO-associated anomalies are strong, the climatic variations in the south central Pacific Ocean strongly reflect the variability of the

ENSO phenomenon since 68% of ENSO events listed by both COADS and Quinn (1992) are registered by the Moorea climatology'.

A.17. Raratonga

Porites lutea growing in 18.3 m of water sampled for Sr/Ca at 1-mm intervals. Chronology established by assuming annual minima in Sr/Ca occurred in February (month of average warmest SSTs) and annual maxima in Sr/Ca in August/September (the months of coldest average SSTs). Twelve values of Sr/Ca derived for each year. Authors report significant correlation (over an unspecified time period) between annual average Sr/Ca and instrumental SSTs of 0.61–0.67. Authors also note a drop in reconstructed SST by 1–1.5°C from 1726–1765 to subsequent years (NB this change is evident as a cooling of annual average reconstructed SSTs of 1.8°C between 1764 and 1765). They note a similar large excursion of δ^{18}O measured in the same coral and argue that this is evidence of the reliability of this dramatic temperature change and suggest a major SST shift in the South Pacific gyre at this time though do suggest that additional coral records are required to confirm this. Authors also note considerable decadal variability in the record that is not coherent with that observed in the New Caledonia coral record. They suggest that several of the recent decadal excursions similar to PDO.

A.18. Ningaloo Reef

Porites lutea sampled at 2-mm intervals and chronology established from annual density banding patterns and annual cycle of δ^{18}O. Highest δ^{18}O each year assigned to mid-September when average SSTs are coldest. Other points linearly interpolated between each September anchor point to give six values per year. Correlation between δ^{18}O and SSTs was −0.80, 1953–1993 but this includes annual cycle. Correlation of annual average δ^{18}O and SST over same time period was −0.45. Authors report a long-term decrease in δ^{18}O of 0.36‰ which, if purely temperature, would equate with a warming of 1.5°C from 1879 to 1994. No significant periodicities found in ENSO frequency band.

A.19. New Caledonia

Porites lutea sampled at 12 measurements per year in the youngest 40 years and at a frequency of four samples per year over the remainder of the coral. Chronology established from annual density banding pattern. Correlation between monthly δ^{18}O and monthly SSTs, 1967–1991, was −0.88 (i.e. including annual cycle). Correlation of annual average values was −0.57 over same period and −0.56, 1903–1991. Authors suggest that seasonal δ^{18}O variations mainly controlled by SSTs but that salinity may be more important on inter-annual time scales and that this might account for reduced strength of relationship on annual compared with seasonal time scales. Authors report significant correlation between annual δ^{18}O and PDO over the 20th century ($r = 0.55$). They also note only 'modest levels of agreement' between this record and other long coral records from the Pacific and that although 'each time series contains inter-annual and decadal variability, it is a rare occurrence when this variability is shared amongst the various records'. The δ^{18}O record, 1658–1992, included in Mann et al. (1998) Multi-proxy Data Network.

A.20. Houtman Abrolhos Island

Porites lutea sampled every 2 mm to give six to eight samples per year. Chronology established from annual density banding pattern and by tying highest δ^{18}O value each year to month of average coldest SST, mid-September, and then linearly interpolating between these anchor points. Time series of six values per year derived. Authors report significant correlation between these seasonal δ^{18}O values and SSTs of −0.71, 1944–1992 (i.e. including annual cycle), and −0.51 based on annual averages. No significant correlations found with local sea level, rainfall or the SOI. Authors note a long-term decrease of δ^{18}O of −0.26‰ which, if purely temperature, would equate to a warming of 1.4°C over the 199-year record period. Authors suggest that the inferred rise since the 1940s matches observed SST trends and that, therefore, the warming over the whole record period is likely to be real.

References

Alibert, C., McCulloch, M.T., 1997. Strontium/calcium ratios in modern *Porites* corals from the Great Barrier Reef as a proxy for sea surface temperature: calibration of the thermometer and monitoring of ENSO. Paleoceanography 12, 345–363.

Allan, R.J., Reason, C.J.C., Carroll, P., Jones, P.D., 2002. A reconstruction of Madras (Chennai) mean sea-level pressure using instrumental records from the late 18th and early 19 centuries. Int. J. Climatol. 22, 1119–1142.

Allison, N., Tudhope, A.W., Fallick, A.E., 1996. Factors influencing the stable carbon and oxygen isotopic composition of *Porites lutea* coral skeletons from Phuket, South Thailand. Coral Reefs 15, 43–57.

Al-Rousan, S., Al-Moghrabi, S., Patzold, J., Wefer, G., 2002. Environmental and biological effects on the stable oxygen isotope records of corals in the northern Gulf of Aqaba, Red Sea. Mar. Ecol. Prog. Ser. 239, 301–310.

Barnes, D.J., Taylor, R.B., Lough, J.M., 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.

Barnett, T.P., Jones, P.D., 2000. Detection and attribution of recent climate change: A status report. Reply. Bull. Am. Meteor. Soc. 81, 2990–2992.

Barnett, T.P. et al., 1999. Detection and attribution of recent climate change: A status report. Bull. Am. Meteor. Soc. 80, 2631–2659.

Beck, J.W., Edwards, R.L., Ito, E., Taylor, F.W., Recy, J., Rougerie, F., Joannot, P., Henin, C., 1992. Sea-surface temperature from coral skeletal strontium/calcium ratios. Science 247, 644–647.

Biondi, F., Gershunov, A., Cayan, D.R., 2001. North Pacific decadal climate variability since 1661. J. Climate 14, 5–10.

Boiseau, M., 1998. Etude de la variability climatique liee a l'ENSO dans l'ocean Pacifique central sud (Moorea) a partir de traceurs geochimiques contenus dans le squelette d'un scleractiniaire a zooxanthelles (*Porites lutea*). Ph.D. Thesis, University of Paris, 202 pp.

Boiseau, M., Juillet-Leclerc, A., Yiou, P., Salvat, B., Isdale, P., Guillaume, M., 1998. Atmospheric and oceanic evidences of El Nino-Southern Oscillation events in the south central Pacific Ocean from coral stable isotopic records over the last 137 years. Paleoceanography 13, 671–685.

Bradley, R.S., Hughes, M.K., Mann, M.E., 2000. Comments on Detection and attribution of recent climate change: A status report. Bull. Am. Meteor. Soc. 81, 2987–2990.

Briffa, K.R., 1995. Interpreting high-resolution proxy climate data – the example of dendroclimatology. In: von Storch, H., Navarra, A. (Eds.), Analysis of Climate Variability. Applications of Statistical Techniques. Springer-Verlag, pp. 77–94.

Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Harris, I.C., Jones, P.D., Shiyatov, S.G., Vaganov, E.A., 2001. Low-frequency temperature variations from a northern tree ring density network. J. Geophys. Res. 106, 2929–2941.

Charles, C.D., Hunter, D.E., Fairbanks, R.G., 1997. Interaction between the ENSO and the Asian monsoon in a coral record of tropical climate. Science 277, 925–928.

Cobb, K.M., Charles, C.D., Hunter, D.E., 2001. A central tropical Pacific coral demonstrates Pacific, Indian, and Atlantic decadal climate connections. Geophys. Res. Lett. 28, 2209–2212.

Cole, J.E., Fairbanks, R.G., Shen, G.T., 1993. The spectrum of recent variability in the Southern Oscillation: results from a Tarawa Atoll coral. Science 260, 1790–1793.

Cole, J.E., Dunbar, R.B., McClanahan, T.R., Muthiga, N., 2000. Tropical Pacific forcing of decadal variability in the western Indian Ocean over the past two centuries. Science 287, 617–619.

Cook, E.R., 1995. Temperature histories from tree rings and corals. Climate Dyn. 11, 211–222.

Cook, E.R., Palmer, J.G., Cook, B.I., Hogg, A., D'Arrigo, R.D., 2002. A multi-millennial palaeoclimatic resource from *Lagarostrobos colensoi* tree-rings at Oroko Swamp, New Zealand. Glob. Panet. Change 33, 209–220.

Crowley, T.J., 2000. Causes of climate change over the past 1000 years. Science 289, 270–276.

Crowley, T.J., Quinn, T.M., Hyde, W.T., 1999. Validation of coral temperature calibrations. Paleoceanography 14, 605–615.

Delcroix, T., Henin, C., Masia, F., Varillon, D., 2001. Three Decades of In Situ Sea Surface Salinity measurements in the Tropical Pacific Ocean (130°E–70°W, 30°N–30°S). Institut de Recherche pour le Development (IRD) ship-of opportunity (SOP) programs.

Druffel, E.R.M., Griffin, S., 1993. Large variations of surface ocean radiocarbon: evidence of circulation changes in the southwestern Pacific Ocean. J. Geophys. Res. 98, 20249–20259.

Dunbar, R.B., Cole, J.E., 1999. Annual Records of Tropical Systems (ARTS). Pages Workshop Report, Series 99-1, 72 pp.

Dunbar, R.B., Wellington, G.M., Colgan, M.W., Glynn, P.W., 1994. Eastern Pacific sea surface temperature since 1600 A.D.: The δ^{18}O record of climate variability in Galapagos corals. Paleoceanography 9, 291–315.

Evans, M.N., Kaplan, A., Cane, M.A., 1998a. Optimal sites for coral-based reconstruction of global sea surface temperatures. Paleoceanography 13, 502–516.

Evans, M.N., Fairbanks, R.G., Rubenstone, J.L., 1998b. A proxy index of ENSO teleconnections. Nature 394, 732–733.

Evans, M.N., Fairbanks, R.G., Rubenstone, J.L., 1999. The thermal oceanographic signal of El Niño reconstructed from a Kiritimati Island coral. J. Geophys. Res. 104, 13409–13421.

Evans, M.N., Kaplan, A., Cane, M.A., 2000. Intercomparison of coral oxygen isotope data and historical sea surface temperature (SST): potential for coral-based SST field reconstructions. Paleoceanography 15, 551–563.

Evans, M.N., Kaplan, A., Cane, M.A., 2002. Pacific sea surface temperature field reconstruction from coral $\delta^{18}O$ data using reduced space objective analysis. Paleoceanography 17, doi: 10.1029/2000PA000590.

Evans, M.N., Cane, M.A., Schrag, D.P., Kaplan, A., Linsley, B.K., Villalba, R., Wellington, G.M., 2001. Support for tropically-driven Pacific decadal variability based on paleoproxy evidence. Geophys. Res. Lett. 28, 3689–3692.

Felis, T., Patzold, J., 2003. Climate records from corals. In: Wefer, G., Lamy, F., Mantoura, F. (Eds.), Marine Science Frontiers for Europe. Springer-Verlag, pp. 11–27.

Felis, T., Patzold, J., Loya, Y., Fine, M., Nawar, A.H., Wefer, G., 2000. A coral oxygen isotope record from the northern Red Sea documenting NAO, ENSO, and North Pacific teleconnections on Middle East climate variability since the year 1750. Paleoceanography 15, 679–694.

Fisher, D.A., 2002. High-resolution multiproxy climatic records from ice cores, tree-rings, corals and documentary sources using eigenvector techniques and maps: assessment of recovered signal and errors. Holocene 12, 401–419.

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

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., 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. Quat. Sci. Rev. 19, 45–64.

Grottoli, A.G., 1999. Variability of stable isotopes and maximum linear extension in reef-coral skeletons at Kanehoe Bay, Hawaii. Mar. Biol. 135, 437–449.

Grottoli, A.G., 2000. Stable carbon isotopes ($\delta^{13}C$) in coral skeletons. Oceanography 13, 93–97.

Grottoli, A.G., 2002. Effect of light and brine shrimp on skeletal $\delta^{13}C$ in the Hawaiian coral *Porites compressa*: a tank experiment. Geochim. Cosmochim. Acta 66, 1955–1967.

Guilderson, T.P., Schrag, D.P., 1999. Reliability of coral isotope records from the western Pacific warm pool: a comparison using age-optimized records. Paleoceanography 14, 457–464.

Guzman, H.M., Tudhope, A.W., 1998. Seasonal variation in skeletal extension rate and stable isotopic ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) composition in response to several environmental variables in the Caribbean reef coral *Siderastrea sidereal*. Mar. Ecol. Prog. Ser. 166, 109–118.

Heiss, G.A., 1994. Coral reefs in the Red Sea: growth, production and stable isotopes. GEOMAR Rep. 32, 1–141.

Hendy, E.J., Gagan, M.K., Alibert, C.A., McCulloch, M.T., Lough, J.M., Isdale, P.J., 2002. Abrupt decrease in tropical Pacific sea surface salinity at end of Little Ice Age. Science 295, 1511–1514.

Hendy, E.J., Gagan, M.K., Lough, J.M., 2003. Chronological control of coral records using luminescent lines and evidence for non-stationary ENSO teleconnections in northeast Australia. Holocene 13, 187–199.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001. The Scientific Basis. Cambridge University Press.

Hulme, J., 1992. A 1951–80 global land precipitation climatology for the evaluation of General Circulation Models. Climate Dyn. 7, 57–72.

Hurrell, J.W., Trenberth, K.E., 1999. Global sea surface temperature analyses: multiple problems and their implications for climate analysis, modeling, and reanalysis. Bull. Am. Meteor. Soc. 80, 2661–2678.

Jones, P.D., Briffa, K.R., Barnett, T.P., Tett, S.F.B., 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with control-run temperatures. Holocene 8, 455–471.

Jones, P.D., Osborn, T.J., Briffa, K.R., 2001. The evolution of climate over the past millennium. Science 292, 662–667.

Juillet-Leclerc, A., Schmidt, G., 2001. A calibration of the oxygen isotope paleothermometer of coral aragonite from *Porites*. Geophys. Res. Lett. 28, 4135–4138.

Kuhnert, H., Patzold, J., Wyrwoll, K.-H., Wefer, G., 2000. Monitoring climate variability over the past 116 years in coral oxygen isotopes from Ningaloo Reef, Western Australia. Int. J. Earth Sci. 88, 725–732.

Kuhnert, H., Patzold, J., Hatcher, B., Wyrwoll, K.-H., Eisenhauer, A., Collins, L.B., Zhu, Z.R., Wefer, G., 1999. A 200-year coral stable oxygen isotope record from a high-latitude reef off Western Australia. Coral Reefs 18, 1–12.

Le Bec, N., Juillet-Leclerc, A., Correge, T., Blamart, D., Delcroix, T., 2000. A coral $\delta^{18}O$ record of ENSO driven sea surface salinity variability in Fiji (south-western tropical Pacific). Geophys. Res. Lett. 27, 3897–3900.

Linsley, B.K., Wellington, G.M., Schrag, D.P., 2000a. Decadal sea surface temperature variability in the sub-tropical South Pacific from 1726–1997 A.D.. Science 290, 1145–1148.

Linsley, B.K., Dunbar, R.B., Wellington, G.M., Mucciarone, D.A., 1994. A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707. J. Geophys. Res. 99, 9977–9994.

Linsley, B.K., Ren, L., Dunbar, R.B., Howe, S., 2000b. El Nino Southern Oscillation (ENSO) and decadal-scale climate variability at 10°N in the eastern Pacific from 1893 to 1994: a coral-based reconstruction from Clipperton Atoll. Paleoceanography 15, 322–335.

Lough, J.M., 1992. An index of the Southern Oscillation reconstructed from western North American tree-ring chronologies. In: Diaz, H.F., Markgraf, V. (Eds.), El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, pp. 215–226.

Lough, J.M., Barnes, D.J., 2000. Environmental controls on growth of the massive coral *Porites*. J. Exp. Mar. Biol. Ecol. 245, 225–243.

Mann, M.E., 2002. The value of multiple proxies. Science 297, 1481–1482.

Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophys. Res. Lett. 30, doi: 10.1029/2003GL017814.

Mann, M.E., Park, J., Bradley, R.S., 1995. Global interdecadal and century-scale climate oscillations during the past five centuries. Nature 378, 266–270.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392, 779–787.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophys. Res. Lett. 26, 759–762.

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

McConnaughey, T., 1989b. ^{13}C and ^{18}O disequilibrium in biological carbonates: II. In vitro simulation of kinetic isotope effects. Geochim. Cosmochim. Acta 53, 163–171.

McCulloch, M.T., Gagan, M.K., Mortimer, G.E., Chivas, A.R., Isdale, P.J., 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.

Morimoto, M., Abe, O., Kayanne, H., Kurita, N., Matsumoto, E., Yoshida N., 2002. Salinity records for the 1997–98 El Niño from Western Pacific corals. Geophys. Res. Lett. 29, doi: 10.0129/2001GL013521.

Muller, A., Gagan, M.K., McCulloch, M.T., 2002. Early marine diagenesis in corals and geochemical consequences for paleoceanographic reconstructions. Geophys. Res. Lett. 28, 4471–4474.

Oberhuber, W., Kofler, W., 2002. Dendroclimatological spring rainfall reconstruction for an inner Alpine dry valley. Theor. Appl. Climatol. 71, 97–106.

Patzold, J., 1986. Temperature and CO_2 changes in tropical surface waters of the Philippines during the last 120 years: record in the stable isotopes of hermatypic corals. Berichte – Reports, Geol.-Palaont. Inst. Univ. Kiel, No. 12, 92 pp.

Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., Buckely, B.M., Dugarjav, C., Mijiddorj, R., 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. J. Climate 14, 872–881.

Quenouille, M.H., 1952. Associated Measurements, Butterworths Scientific, 242 pp.

Quinn, T.M., Taylor, F.W., Crowley, T.J., 1993. A 173 year stable isotope record from a tropical South Pacific coral. Quat. Sci. Rev. 12, 407–418.

Quinn, T.M., Crowley, T.J., Taylor, F.W., 1996a. New stable isotope results from a 173-year coral record from Espiritu Santo, Vanuatu. Geophys. Res. Lett. 23, 3413–3416.

Quinn, T.M., Taylor, F.W., Crowley, T.J., Link, S.M., 1996b. Evaluation of sampling resolution in coral stable isotope records: a case study using records from New Caledonia and Tarawa. Paleoceanography 11, 529–542.

Quinn, T.M., Crowley, T.J., Taylor, F.W., Henin, C., Joannot, P., Join, Y., 1998. A multicentury stable isotope record from a New Caledonia coral: interannual and decadal SST variability in the southwest Pacific since 1657. Paleoceanography 13, 412–426.

Quinn, W.H., 1992. A study of Southern Oscillation-related climatic activity for A.D. 622-1990 incorporating Nile River flood data. In: Diaz, H.F., Markgraf, V. (Eds.), El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, pp. 119–149.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C., Kaplan, A., 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperatures since the late nineteenth century. J. Geophys. Res. 108, doi: 10.1029/2002JD002670.

Ren, L., Linsley, B.K., Wellington, G.M., Schrag, D.P., Hoegh-Guldberg, O., 2002. Deconvolving the δ^{18}O seawater component from subseasonal coral δ^{18}O and Sr/Ca at Raratonga in the southwestern subtropical Pacific for the period 1726 to 1997. Geochim. Cosmochim. Acta 67, 1609–1621.

Trenberth, K.E., Otto-Bliesner, B.L., 2003. Toward integrated reconstruction of past climates. Science 300, 589–591.

Tudhope, A.W., Shimmield, G.B., Chilcott, C.P., Jebb, M., Fallick, A.E., Dalgeish, A.N., 1995. Recent changes in climate in the western equatorial Pacific and their relationship to the Southern Oscillation; oxygen isotope records from massive corals, Papua New Guinea. Earth Planet. Sci. Lett. 136, 575–590.

Tudhope, A.W., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R.T., Lea, D.W., Lough, J.M., Shimmield, G.B., 2001. Variability in the El Nino-Southern Oscillation through a glacial–interglacial cycle. Science 291, 1511–1517.

Urban, F.E., Cole, J.E., Overpeck, J.T., 2000. Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record. Nature 407, 989–993.

Watanabe, T., Winter, A., Oba, T., Anzai, R., Ishioroshi, H., 2002. Evaluation of the fidelity of isotope records as an environmental proxy in the coral *Montastraea*. Coral Reefs 21, 169–178.

Wellington, G.M., Dunbar, R.B., Merlen, G., 1996. Calibration of stable oxygen isotope signatures in Galapagos corals. Paleoceanography 11, 467–480.