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Monsoon–tropical ocean interaction in a network of coral records spanning the 20th century

Christopher D. Charles[a,*], Kim Cobb[a,1], Michael D. Moore[a,2], Richard G. Fairbanks[b]

[a] *Scripps Institution of Oceanography, La Jolla, CA 92093, USA*
[b] *Lamont Doherty Earth Observatory, Palisades, NY 10964, USA*

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Abstract

The 20th century evolution of basin-wide gradients in surface ocean properties provides one essential test for recent models of the interaction between the Asian monsoon and the tropical ocean, because various feedback mechanisms should result in characteristic regional patterns of variability. Although the instrumental record of climate variability in the tropics is essentially limited to the last few decades, the stable isotopic composition of living corals provides an effective means for extending the instrumental observations. Here we present two coral isotopic records from the Indonesian Maritime Continent, and we use these records with other previously published records to describe: (i) the relationship between western Pacific and central Pacific climate variability over the past century, with special emphasis on the biennial band; and (ii) the strength of the west–east 'Indian Ocean Dipole'. We find that the amplitude of the biennial cycle in the Pacific did not vary inversely with the strength of ENSO (El Niño Southern Oscillation), as might be expected from some models of monsoonal feedback on the central Pacific. Instead, the biennial variability was modulated on decadal timescales throughout much of the Pacific. We also show that the zonal oxygen isotopic gradient in the Indian Ocean coral records was significantly correlated with central Pacific sea surface temperature on a variety of timescales. Thus, it is likely that this 'coral dipole' was a product of strong ENSO-like teleconnections over the Indian Ocean, as opposed to being the result of unique Indian Ocean or monsoonal dynamics.

Keywords: climate changes; coral reefs; isotope ratios; El Niño

1. Introduction

The Asian monsoon and the tropical Pacific Ocean are often treated independently in considerations of past climate change. Yet, because these components of the climate system guide the largest centers of convective activity on the planet, their interaction is likely to be important

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[1] Present address: California Institute of Technology, Pasadena, CA 91125, USA.
[2] Present address: EcoReefs, 219 Miguel Street, San Francisco, CA 94131, USA.
* Corresponding author. Tel.: +1-858-822-3310.
E-mail address: ccharles@ucsd.edu (C.D. Charles).

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for determining tropical climate variability over a wide spectrum of timescales. Each of these components is highly complex in their own right, and, therefore, so is any analysis of their interplay. The most obvious example of this complexity is the fact that the correlations between indices of the South Asian monsoon and the El Niño Southern Oscillation (ENSO) tend to evolve, apparently over decades to centuries (e.g. Torrence and Webster, 1999; Kumar et al., 1999). However, the general problem of monsoon–tropical Pacific interaction is important, because it bears directly on the question of long-range global climate predictability. Furthermore, even if their interaction ultimately is viewed as being chaotic or stochastic, the statistics of these components of the climate system represent a critical aspect of the response of the tropics to any external forcing: climate models show clearly that changes in the frequency and amplitude of interannual variability in the tropics can give rise to changes in the mean state of global climate over thousands of years (e.g. Clement et al., 1999).

Various possible mechanisms of interaction between the monsoon and the tropical Pacific have been established from examination of the instrumental record of climate. The general negative correlation between the indices of the Asian summer monsoon and ENSO warm events over the last 150 years implies that the behavior of the tropical Pacific can influence the strength of the monsoon directly through the perturbation of the Walker circulation (Webster et al., 1998, among many others). On the other hand, analyses of the most recent decades of the instrumental record emphasize the capacity for the East Asian monsoon to influence the evolution of ENSO, by the action of western Pacific winds (Lau, 2001). For example, if the monsoonal wind feedback mechanism outlined by Kim and Lau (2001) is an omnipresent part of the climate system, then the implication is that the monsoon could act as a 'pacemaker' for ENSO, damping interannual variability and imposing a biennial cycle across the tropical Pacific. Along separate, but analogous lines, detailed dissection of the 1997/98 warm event and other recent climate oscillations suggest the possibility that the dynamics of the Indian Ocean influences monsoonal processes and, therefore, the relationship between the Indian summer monsoon and ENSO (Webster et al., 1999; Saji et al., 1999).

One simple, yet powerful test of these mechanisms is to gauge their operation under significantly different global climate conditions: individually, ENSO and the monsoon must be sensitive to different external forces, and, therefore, the contrasting strength of the individual components offers the means for describing possible interactions. This test is difficult to perform with the instrumental record alone, because in most tropical regions, continuous time series only extend several decades. And the few available indices that do cover a significant timespan may or may not be diagnostic of large-scale processes (Wang and Fan, 1999). The purpose of this paper is to describe monsoon–ocean interactions over the last century that are expressed in a collection of long, monthly resolved coral records collected from key regions of the tropical Pacific and Indian oceans. Previous analyses of coral oxygen isotope time series demonstrate that these proxy records can capture the essential features of tropical surface climate variability with fidelity that rivals instrumental records (e.g. Cole et al., 1993; Fairbanks et al., 1997). While it is difficult to build fields of observations using records from single sites – a basic limitation of any geological archive – the advantage of corals is that they provide continuous time series that are not biased systematically by the recording process. By contrast, it is often difficult to equate early 20th century instrumental observations with those taken later in the century. The instrumental and coral approaches can be combined effectively, if the rich spatial distribution of observations from the modern climate guides the development of temporally extended proxy records from the most sensitive regions of the tropics.

Here we present two stable isotope records from sites located on the Pacific and Indian Ocean margins of the Indonesian Maritime Continent. We analyze these records in conjunction with other analogous records from established 'centers of action' in the central Pacific Ocean and western Indian Ocean. The records all span more than a

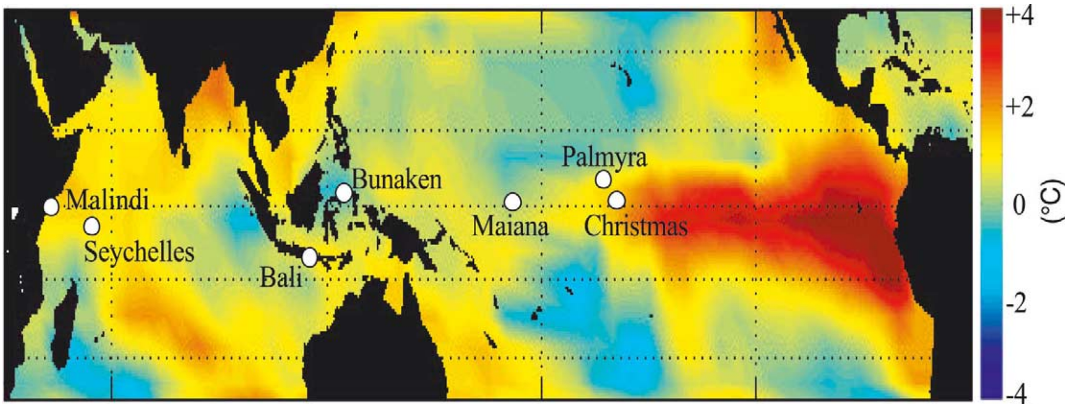

Fig. 1. Map of coral core locations superimposed on the December, 1997 ENSO SST anomaly field (from Reynolds et al., 2002) illustrating the varying sensitivities of each site. The sources of coral data from each site are as follows: Kirimati (Evans et al., 1999); Palmyra (Cobb et al., 2001); Maiana (Urban et al., 2000); Bunaken (this work); Bali (this work); Seychelles (Charles et al., 1997); Malindi (Cole et al., 2000).

century, and they capture pre-industrial climate, as well as the extended period of low ENSO variability (from 1910 to 1950). The emphasis of our description here will be the evolution of the biennial character and decadal modulation of interannual climate change. Both these aspects of tropical climate change should bear perhaps the clearest stamp of monsoon–ENSO interaction (Meehl, 1997). In a broader perspective, regardless of timescale, the records illustrate the utility of oxygen isotopes for describing zonal gradients in climate across the tropics.

2. Materials and methods

The coral records assembled here were collected for the purposes of creating extended time series from regions of strong interannual climate variability (Fig. 1). Though they were produced by separate laboratories, the coral time series were all generated using standard techniques. Living *Porites* coral colonies were drilled in 3–5 m of water. The cores were slabbed, X-rayed and sampled at 1 mm intervals, along transects normal to the growth axis. These massive corals grow 1–2 cm per year, and, therefore, the sampling scheme of the cores typically achieves monthly resolution. The samples were analyzed for stable isotopes (oxygen and carbon), with a long-term precision that, for the SIO laboratory, is better than 0.08 ‰ and 0.06 ‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Some of the corals have been analyzed for minor element chemistry as well as for isotopes. However, for consistency, we will limit our consideration here to only the $\delta^{18}O$ records. The chronologies for each individual core were developed by following the seasonal cycle in isotopes, assigning the maxima and minima to particular months of the year (according to the climatology of a particular site), then interpolating between these seasonal extreme anchor points. The error on any coral chronology is on the order of several months for any given year. This chronological uncertainty implies that, although corals can record climate anomalies throughout the year, they are not well-suited to test any mechanism that relies on the precise phasing of those anomalies with respect to the seasonal cycle (which is possibly a key aspect of Southeast Asian monsoon–ENSO feedback).

The $\delta^{18}O$ of coral skeletons depends on both the temperature and the isotopic composition of the ambient seawater. In the central Pacific and western Indian Ocean, the interannual variability in the coral $\delta^{18}O$ time series is primarily a measure of sea surface temperature (SST) (Fairbanks et al., 1997; Evans et al., 1999; Cobb et al., 2001). In the Indonesian coral records, coral $\delta^{18}O$ is more heavily influenced by rainfall variability (as

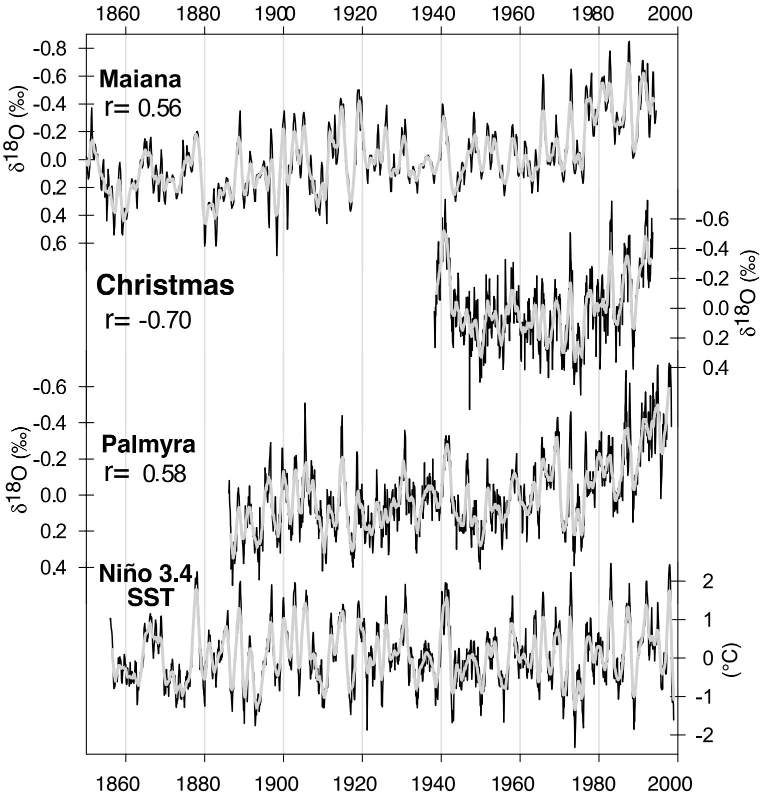

Fig. 2. Monthly time series of coral oxygen isotope anomalies from the central tropical Pacific. The correlation *r* value is shown with respect to reconstructions of the instrumental record of Niño 3.4 SST (Kaplan et al., 1998). The heavy line in each case is a 13-month smoothed series.

we will illustrate here, and as described by Moore, 1995). This dual sensitivity of $\delta^{18}O$ complicates potential quantification of long-term (century scale) temperature trends, a subject that we will not address here. But in most regions of the tropics, rainfall anomalies are usually highly correlated with SST change. As a result, it is often not necessary to disentangle the different influences on this proxy for the purposes of reconstructing interannual surface climate variability.

3. Results

In the sections to follow, we illustrate the essential climatic characteristics of each of the sites considered, as well as the capacity for coral $\delta^{18}O$ to record the regional climatic variability. The majority of this site-specific description will deal with the Indonesian coral records that have not been presented elsewhere. Subsequently, we describe interbasinal climatic gradients and trends that are relevant to the issue of monsoon–ENSO interaction.

3.1. *Central Pacific and western Indian Ocean*

Previous work demonstrates clearly that coral $\delta^{18}O$ time series from the central Pacific can be used to extend and complement the instrumental record of the ENSO phenomenon (e.g. Cole et al., 1993; Evans et al., 1999; Urban et al., 2000; Cobb et al., 2001) For example, in the interannual band, the overall statistics of these records are nearly identical to those of the reconstructions of instrumental ENSO indices such as Niño 3.4. This observation lends credibility to both the instrumental and proxy reconstructions, but contin-

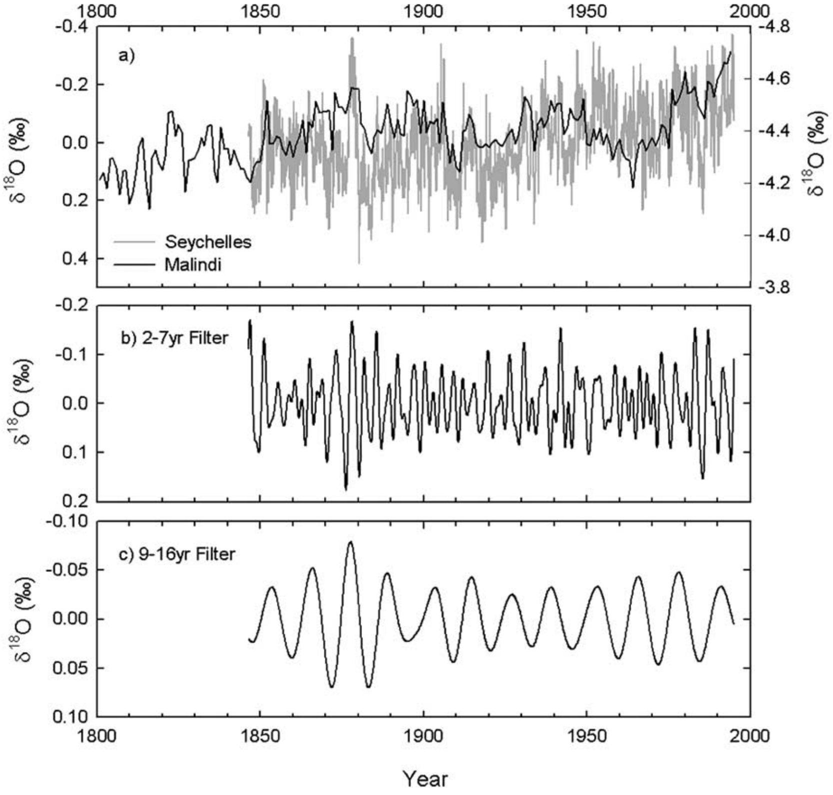

Fig. 3. (a) Time series of coral oxygen isotope records from the western Indian Ocean. Monthly anomalies and annual average values are shown for Seychelles and Malindi, respectively. (b) ENSO (3–7 year band) filter of the Seychelles record, plotted with the same filter of Niño 3.4 SST. (c) Decadal (10–16 year band) filter of the Seychelles record.

uous time series from corals are especially valuable because the number of instrumental observations drops considerably before 1950. Thus, coral records provide a continuous picture of the evolution of ENSO over at least the 20th century (Fig. 2). The main features of that 20th century variability are the diminished overall amplitude of ENSO during the period from 1910 to 1950, and a shift to lower frequency of warm events during the middle part of the century – features that appear strongly in both instrumental and proxy records. The coral records all display a strong century-scale trend that is not apparent in the Niño 3.4 temperature index. As yet, we cannot make much of this observation (even though, in principle, the difference might reflect changes in the hydrological cycle or tropical ocean dynamics) because neither the coral $\delta^{18}O$ trends nor the trends in the observations can be considered a reliable indication of real SST trends. For our purposes here, we can at least assert that each of the coral records has unique qualities, and the differences among records are, most likely, a product of the real geographic expression of ENSO variability. We will consider the variability that is common to all the records when using them for generic indices of ENSO activity. However, as more records become available, the differences among them could ultimately lead to a refined understanding of the mechanisms of lower frequency change or the modulation of ENSO strength.

Previously published coral records from sites in the western Indian Ocean (Fig. 3) also reflect the evolution of ENSO, suggesting a strong teleconnection between the Pacific and Indian basins (Charles et al., 1997; Cole et al., 2000). Interannual anomalies in western Indian Ocean $\delta^{18}O$

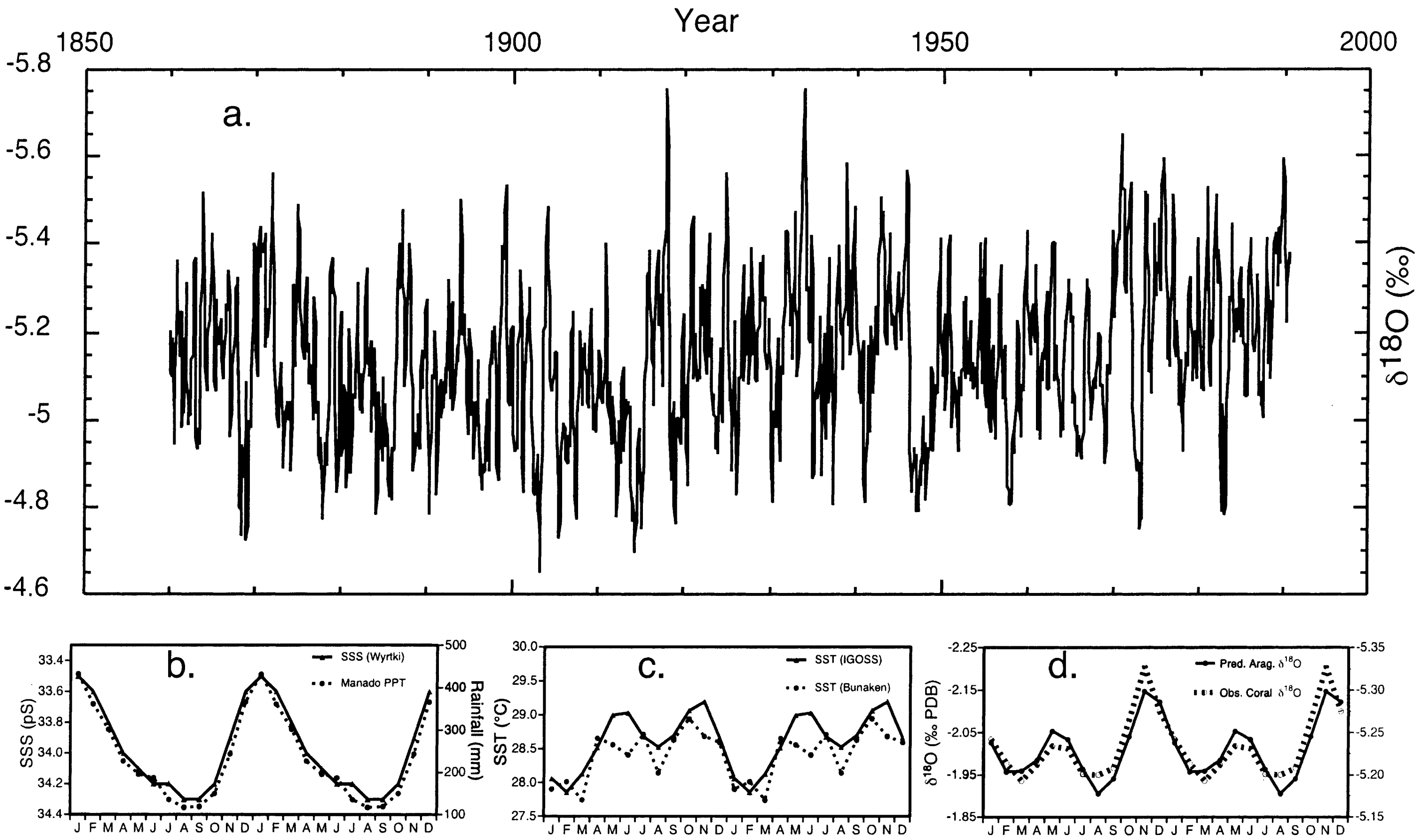

Fig. 4. (a) The monthly coral $\delta^{18}O$ time series from Bunaken Island (N. Sulawesi), for the years 1863–1990. (b,c) Atlas-derived estimates of the annual climatology of the site for the variables that contribute to the $\delta^{18}O$ signal. The source of the atlas data is as follows: Wyrtki (Wyrtki, 1961); IGOSS (Reynolds et al., 2002); Levitus (Levitus et al., 1994). (d) Predicted climatology of coral $\delta^{18}O$ using the temperature and salinity estimates and the Epstein et al. (1953) paleotemperature equation, along with the observed coral $\delta^{18}O$ climatology for the years 1960–1990.

(and SST) are significantly coherent with those of the central Pacific; the phase is such that the Indian Ocean response appears to lag the central Pacific by several months. Another important feature of the Indian Ocean coral records is the strong periodicity in the decadal bands. Charles et al. (1997) speculated that the source of this decadal variability lies in the coupling between the South Asian monsoon and the Indian Ocean. However, it is now clear that this variability is highly coherent with decadal climate fluctuations throughout the tropics (Cole et al., 2000; Cobb et al., 2001), therefore bringing in a wider range of possible explanations. Western Indian ocean coral anomalies that are filtered at decadal periods appear to lead (by 1–2 years) those of central Pacific – an observation, which, at face value, suggests a propagating phenomenon or an effect that is activated by the change from one extreme state in the Pacific to another (Cobb et al., 2001).

3.2. Bunaken, Indonesia

Bunaken Island lies on the periphery of the zone dominated by monsoonal circulation, and the magnitude of the seasonal $\delta^{18}O$ response resembles that of the open ocean conditions of the western Pacific. On interannual timescales, the site is characterized generally by cooler, drier conditions during ENSO warm phases. Rainfall stations on the north Sulawesi coast show deficits of 40–50% during these times, and the SST cools by several tenths of a degree, essentially the opposite climate response to that of the eastern Pacific and South China Sea. If the dynamics of the western Pacific are critical to the linkage between the east Asian Monsoon and ENSO, then this site should be favorable for retrospective monitoring of those key processes.

A single 2.65 m core from a large *Porites* growing at 3 m was collected from the windward coast of Bunaken Island, (1°30′N, 124°50′E) in August 1990, and continuous sampling of the core yielded a 127-yr monthly resolution stable isotope time series. An annually averaged record from this same coral was published in Moore et al. (2000). The full monthly Bunaken $\delta^{18}O$ time series (Fig. 4a) is weakly seasonal with strong interannual variability. A chronology for the complete Bunaken coral record was developed by anchoring seasonal maxima and minima of the $\delta^{18}O$ depth series to March and October of each year. Cross-checks on the age assignments were available through examination of the annual growth bands and the strong semi-annual carbon isotope signal (data not shown).

The annual variability of the Bunaken coral $\delta^{18}O$ reflects the seasonal cycle of both salinity and temperature in the surrounding seawater. The average measured coral $\delta^{18}O$ seasonality captures the predicted seasonal cycle with considerable fidelity (Fig. 4d), demonstrating, among other things that the resolution of the record is near-monthly and that the coral chemistry reflects open-ocean conditions.

ENSO warm phases are typically expressed around the Maritime Continent as SST anomalies of −0.5°C and precipitation deficits of roughly 50%. Precise calibration of the expected coral signal is difficult without continuous $\delta^{18}O$ seawater measurements, but general scaling of the instrumental record suggests that such shifts should result in coral $\delta^{18}O$ anomalies of +0.19‰, representing a 50% reduction in $\delta^{18}O$ seasonality. Thus, the Bunaken $\delta^{18}O$ record should be highly sensitive to interannual variability, and comparison to the indices of both local-scale and regional-scale convection bears out this sensitivity. Discontinuous local rainfall data for Manado Port (10 km from Bunaken Island) are available to 1879. The Bunaken $\delta^{18}O$ record correlates well ($r = 0.59$) with this local precipitation record for the intervals when the observations exist (Fig. 5A). The record is also significantly correlated with Darwin Sea Level Pressure Anomaly (SLPA; not shown) in the 3–7 year ENSO frequency band. ENSO warm phases are marked by positive $\delta^{18}O$ anomalies; the Bunaken $\delta^{18}O$ record captures nearly all of the major ENSO warm phases observed by the Darwin SLPA record.

In addition to the basic sensitivity to ENSO phase changes, this coral record shows a very strong biennial tendency (Fig. 5B). Taking the record as a whole, the amplitude of biennial variability is more prominent in the Bunaken record than it is in the coral records from the central

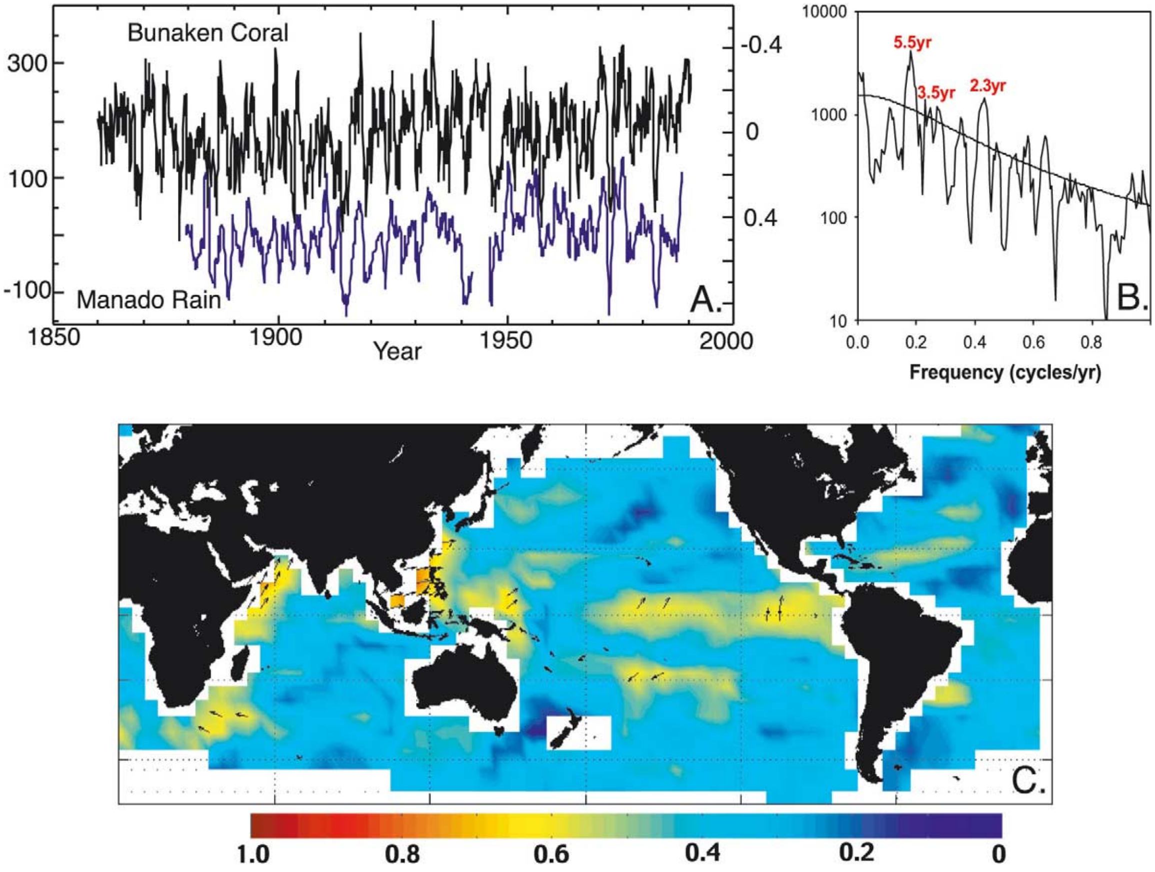

Fig. 5. (A) The monthly coral $\delta^{18}O$ anomalies (with the seasonal cycle removed) from Bunaken Island, along with a 13-month smoothed rainfall record from nearby Manado Port. The correlation, *r*, between the two series is 0.59. (B) The spectrum of the Bunaken coral record, illustrating the significant concentration of power in the biennial band; the smooth line is the 95% significance level for a red noise spectrum. (C) Coherence between the Bunaken coral $\delta^{18}O$ and gridded SST observations (Rayner et al., 1996) for the years 1920–1992, filtered in the biennial band (1.8–2.6 year). Arrows denote the phase with respect to Bunaken for those gridboxes where the coherency is statistically significant at the 90% confidence level. Arrows pointing due north denote zero phase.

tropical Pacific (as shown in later figures; after removing the seasonal cycle, the biennial band comprises 12% of the variance, as opposed to less than 10% for the central Pacific corals). Furthermore, the biennial variability in the Bunaken record is highly coherent with available instrumental SST observations from the marginal seas that are dominated by monsoonal processes – for example, the South China Sea (Fig. 5C). The biennial variability in the coral appears to lead the temperature in the marginal seas by several months, with drier, cooler conditions at this site corresponding to warm SSTs in the South China Sea. Thus, this biennial aspect of the coral record most likely reflects the more localized influence of Southeast Asian monsoonal variability, and more remotely, the activity of the so-called West Pacific Anticyclone centered to the north over the Philippine Sea.

3.3. *Padang Bai (Bali), Indonesia*

This site lies in the most distal portion of the Indonesian throughflow, just adjacent to the Indian Ocean margin of the Maritime Continent, in the Lombok Strait (8°15′S, 115°30′E). Like Bunaken, this area generally experiences drought during ENSO warm phases, but the interannual/decadal variability in SST is not identical to that for the western equatorial Pacific. In fact, this site lies within the broad region of the eastern Indian Ocean that comprises one part of the 'Indian Ocean Dipole' that is apparent from analysis of coupled temperature and rainfall patterns over the past two decades (Lau, 2001). Recent CTD moorings deployed close to the coral site show that western Lombok Strait registers some of the initial effects of the seasonal upwelling that characterizes the equatorial eastern Indian Ocean later in the year (Sprintall et al., 2003). Therefore, this site should provide a useful comparison with the sites from the western Indian Ocean for a perspective on the evolution of the Indian Ocean Dipole structure and its relationship with monsoonal variability.

Multiple cores were drilled in 1990 from an exceptionally large *Porites* colony growing at a depth of 5 m off Padang Bai. The longest core sampled nearly 300 years of growth. However, petrographic analyses of the lowermost portion of the core revealed the presence of secondary aragonite infilling that adversely affected the quality of the isotopic record. Therefore, we limit our consideration to the pristine sections of the core that span 1783–1990 AD. Chronological assignments for the record were generally straightforward, because of the clear seasonal cycle in δ^{18}O and the especially clear expression of annual growth bands. The seasonal extremes were anchored to April and September of each year.

The Bali δ^{18}O time series is strongly seasonal – much more so than at Bunaken, in accordance with the greater seasonal cycle in SST in the Lombok Strait (roughly 3°C at this site; Sprintall et al., 2003). But there is also significant interannual variability in the coral record, showing general sensitivity to ENSO with the same polarity as with much of Indonesia: ENSO warm phases are marked by positive δ^{18}O excursions, reflecting, at least in part, the weakening and dislocation of the Indonesian low-pressure cell (Fig. 6A). The Indonesian throughflow water that exits the Lombok Strait also carries an ENSO signal in temperature and salinity, though the influence of this signal is strongest below the surface mixed layer (Ffield et al., 2000). The sensitivity of the coral record with respect to regional ENSO-related changes is readily apparent from its coherency and phase with respect to other instrumental observations over the interannual band, such as the Darwin SLP (Fig. 6B).

However, a combination of simple visual inspection, cross-spectral analysis (not shown) suggests that the Bali record is distinct from Bunaken in the biennial–interannual bands. The biennial tendency is not as consistent, and significant power exists in the Bali record only at periods of 32 months (not shown), as opposed to 28 months in the case of Bunaken (and the South China Sea). Thus, the Bali record evidently monitors unique local influences, in addition to the Indonesian-wide response to ENSO. Two specific examples of this generalization occur in the years 1961 and 1967, when the Bali coral recorded high δ^{18}O (indicating lower temperatures or higher salinity), despite neutral or La Niña conditions in the Pacific. The events in these years have been taken as anecdotal evidence (Saji et al., 1999) for the existence of a unique Indian Ocean Dipole (a subject that we address in more detail below), but we point to these years simply to suggest that the Bali record is not necessarily a direct reflection of ENSO-related rainfall variability only.

This generalization also extends to the decadal and interdecadal bands, where the Bali record shows evidence for pronounced low-frequency variability, particularly in the 19th century. A significant concentration of variance apparently lies in the tidal frequencies (18.6 and 9.3 years), which is perhaps not suprising given the tidal influences on the currents in the area (Murray and Arief, 1988; Sprintall et al., 2003). However, the record shows prominent variance at periods of 26 and 13 years, periodicities that also appear in coral records from the western Indian Ocean (as mentioned previously). The 13-year periodicity is also characteristic of one principal mode of coupled SST and rainfall variability in the region (Lau, 2001).

Taken together with the evidence from the interannual bands, the decadal signature of the Bali record suggests that it captures many of the essential features of eastern Indian Ocean climate. Thus, we will use it here as a temporally extended index of one center of the Indian Ocean Dipole, recognizing that it may not be the cleanest possible representation of the equatorial eastern Indian Ocean SST variability. Corals from off Sumatra would perhaps be preferable for this purpose, but, currently, long records from that region do not exist.

3.4. *Southeast Asian monsoon–tropical Pacific interactions*

Having demonstrated that our coral sites are appropriate for resolving broad regional climate processes, we are now in a position to examine basin-scale variability in the network of records. The first comparison involves the relationship between the Indonesian and central Pacific corals. If recent models of Southeast monsoonal feedback are correct, then there are several predictions for the temporal evolution of climate in the central Pacific and the Indonesian Maritime Continent that should be apparent in coral proxy records. For example, one might expect to find an alternation between the patterns associated with biennial oscillations and those of ENSO, depending upon the varying strength of the monsoon–tropical Pacific interaction.

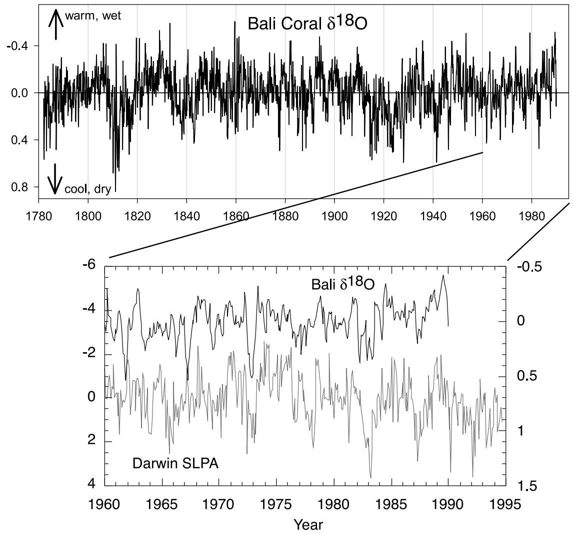

Fig. 6. (a) Monthly coral from Padang Bai, Bali, covering the period 1783–1990. (b) Expanded view of the last 30 years of the Bali $\delta^{18}O$ anomalies record, plotted along with that of Darwin SLPA.

Filtered coral records from both the central Pa-

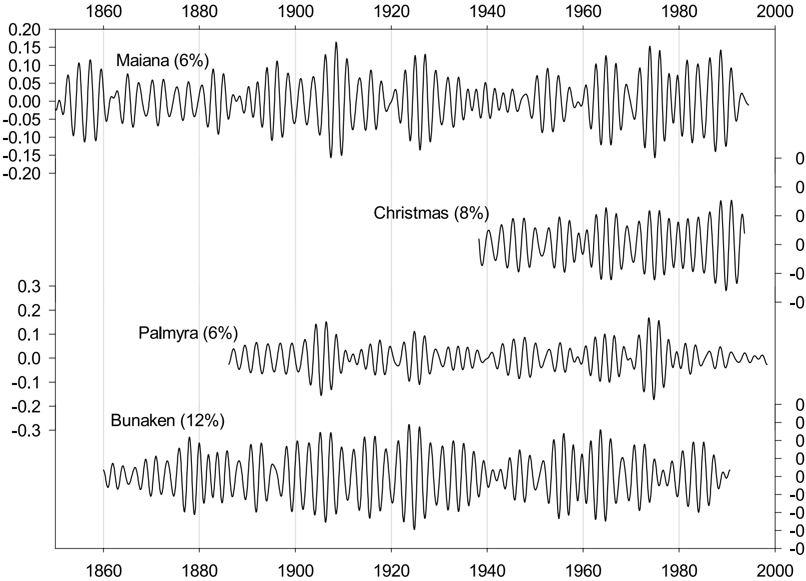

Fig. 7. Biennial band filters (1.8–2.6 years) of coral records from the central Pacific and Indonesia. Note the decadal modulation of the amplitude in the central Pacific records.

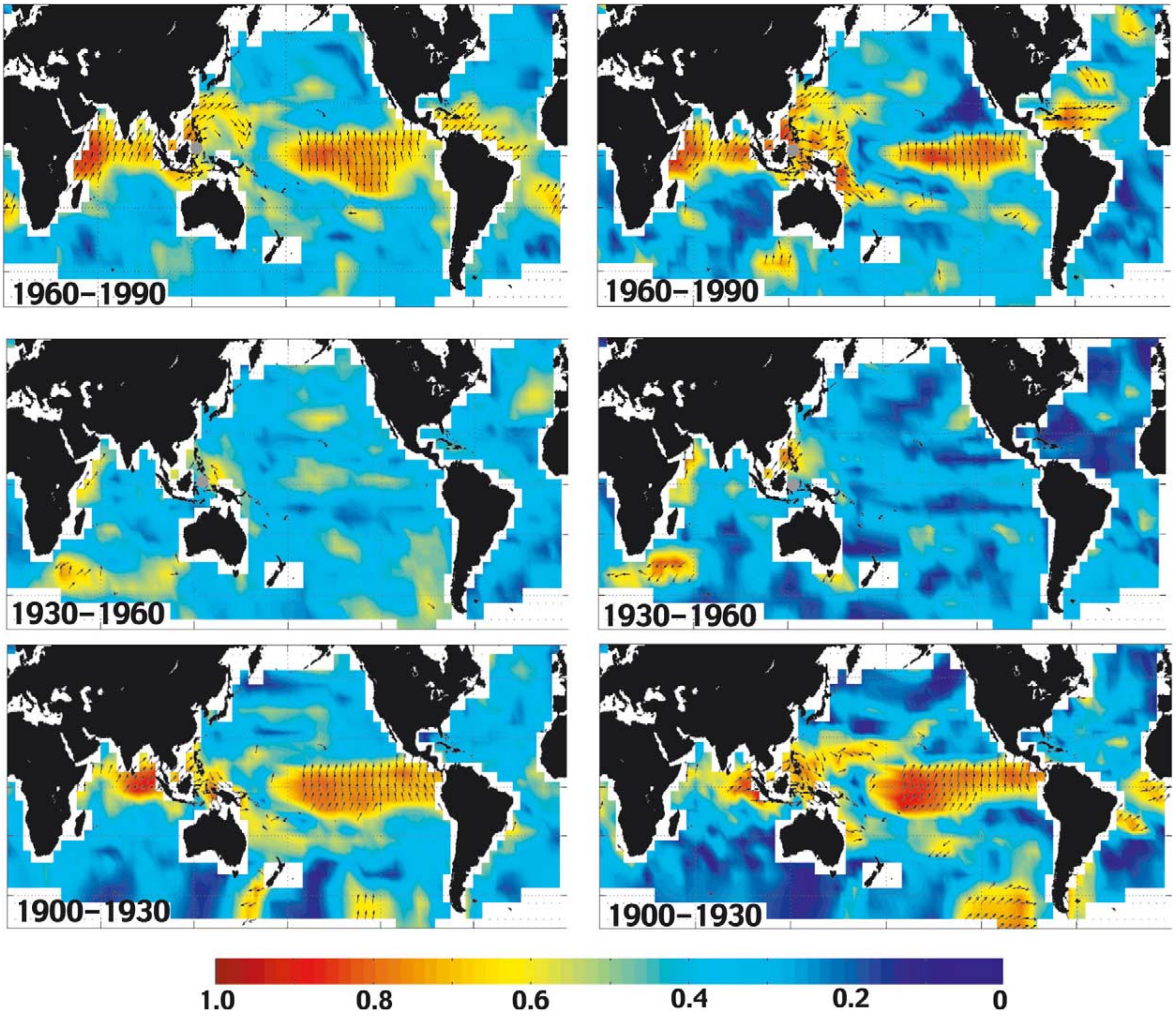

Fig. 8. Same as Fig. 5C, except the analyses were conducted for the separate epochs as indicated, and the left panels show the ENSO band (2–7 years) results for comparison.

cific and from Indonesia suggest that the trade-off between ENSO frequencies and biennial frequencies was not so simple (Fig. 7). For example, in the central Pacific, there were occasional periods of increased biennial variability throughout the 20th century, but they did not correspond clearly with the extended periods of decreased ENSO activity. If anything, the biennial tendency in the central Pacific was generally weak when ENSO was weak. On the whole, the energy in the biennial band in the central Pacific corals is strongly modulated on decadal timescales (cf. the Maiana and the Palmyra records). This modulation is characteristic of sea-level pressure records sensitive to the Southern Oscillation phenomenon (e.g. Barnett, 1989), but it is not a significant feature of the Bunaken coral records or instrumental SST records from the western Pacific ‘warm pool’.

To expand these observations beyond the individual coral time series, we separated atlas instrumental SST observations into epochs of ‘weak’ biennial variability and ‘strong’ biennial variability, as identified by the filtered coral records – the intervals 1930–1960 versus 1900–1930 and 1960–1990 – and performed the identical coherency analysis as in Fig. 5 (again using the Bunaken coral record as the target for comparison). We also examined these same intervals for coherency in the ENSO band. The results (Fig. 8) show that, from 1930 to 1960, the biennial variability in the western Pacific and marginal seas was essentially uncorrelated with that observed elsewhere throughout the Pacific. By contrast, significant coherency exists between the Bunaken coral time series and SSTs across much of the tropical Pacific in both the earlier and later epochs. A similar conclusion can be reached for the interannual frequency band, and, in the context of these analyses, the only discernible difference between the two frequency bands lies in the specific coherencies calculated for the warm pool region (compare the two frequency bands in, for example, the SW Pacific warm pool region in the 1960–1990 interval).

The details of the correlations prior to 1960 should not be interpreted too finely, because in many parts of the tropical Pacific the observations are discontinuous, and, therefore, the filtering may produce spurious results. However, the gross features of the epochal patterns are probably legitimate, especially because the coral records alone lead to the same general picture: the coherency between the western Pacific and central Pacific climate was weak in the middle of the century, when the total amplitude of biennial and interannual variability was reduced across the entire Pacific.

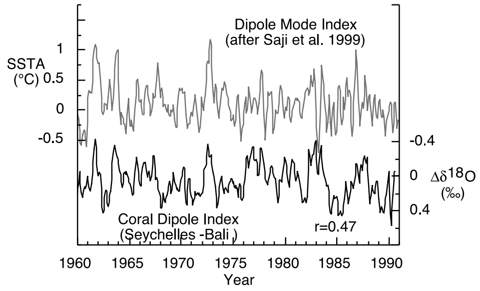

Fig. 9. The West–East Indian Ocean 'Dipole Mode Index', of SST, defined by Saji et al. (1999), compared with the difference between Seychelles–Bali monthly coral oxygen isotope anomalies, both smoothed with a 5 pt. running mean. The correlation, r, is as indicated and would be higher with fine-scale adjustments to the coral chronologies.

3.5. *Dynamics of the southern tropical Indian Ocean*

Recent discussions of interannual climate change in the Indian Ocean have centered on the processes that produce the Indian Ocean Dipole, the dominant expression of coherent variability across the equatorial and southern tropical Indian Ocean. Using coral records, we take the $\delta^{18}O$ difference between western Indian Ocean (Seychelles) and eastern Indian Ocean (Bali) to monitor the strength of the dipole in the southern tropical Indian Ocean. These records allow the development of a 150-year index of the general basinal pattern that is associated with coupled rainfall/SST variability. We present the simple arithmetic difference between the two sites, but similar results are obtained if one first normalizes the records individually.

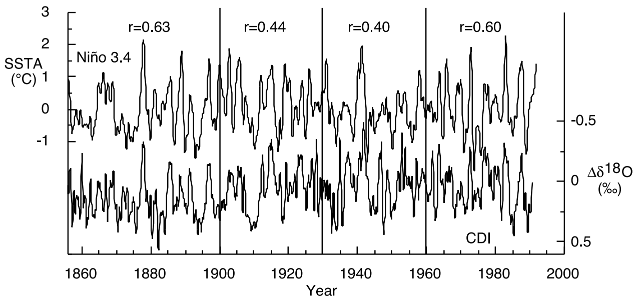

Fig. 10. (a) The CDI (as in Fig. 8), with the reconstruction of Niño 3.4 SST (from Kaplan et al., 1998), both smoothed with a 13-month running mean. The correlations for each of the 30-yr epochs are shown.

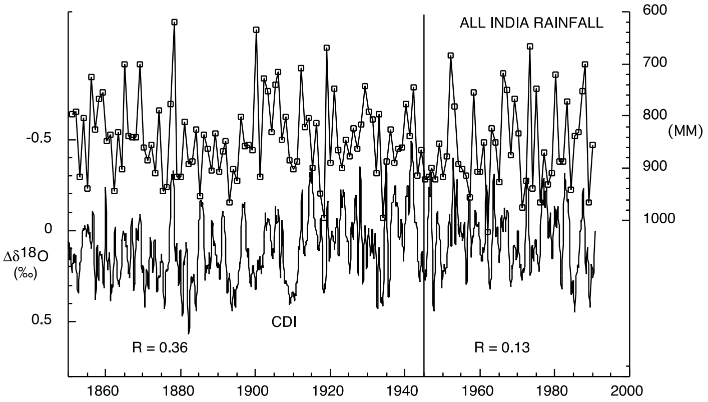

Fig. 11. The CDI with the All India Rainfall Index of summer monsoon strength, lagged by 4 months (for ease of viewing). The correlation for separate epochs is as indicated. The overall correlation would improve with fine-scale (seasonal) chronological adjustments to the coral index.

The coral index reproduces the features of the instrumental SST 'dipole mode index' (Saji et al., 1999) with reasonable fidelity over the last 30 years (Fig. 9). The most prominent feature of the extended coral dipole index (CDI) is the especially strong periodicity at 12–13 years (Fig. 9). Lower-frequency variability (interdecadal to centennial) is not nearly as obvious in this index, probably because the longer-period trends are expressed similarly in both coral records and therefore cancel each other when differenced. Aside from the decadal variability, the ENSO and biennial frequencies also stand out clearly: stronger west–east gradients in $\delta^{18}O$ are associated with ENSO warm events.

The comparison of this CDI to those of central tropical Pacific SSTs (Fig. 10) and South Asian monsoon strength (Fig. 11) reveals several aspects of the evolution of the monsoon/tropical Pacific relationship and therefore provides strong clues about the mechanisms responsible for maintaining the Indian Ocean Dipole pattern. Considering the various indices in their entirety, the CDI is significantly correlated with both AIRI and Niño 3.4. On interannual timescales (2–7 years), the phase of the CDI is indistinguishable from the central Pacific SST, while the coral anomalies appear to lag anomalous summer rainfall by several months. On decadal timescales (9–16 years), the phase difference between the CDI and Niño 3.4 is approximately 2 (±1) years, as was the case in Cobb et al.'s (2001) analogous comparison. Breaking the records into epochs, there is strong correlation between the CDI and reconstructions of Niño 3.4 between 1860 and 1895, and equally strong correlations after 1960. The correlation between CDI and Niño 3.4 in the interval 1900–1960 was significantly weaker, and this decreased correlation generally corresponds with the decrease in ENSO energy. With respect to monsoonal rainfall, the correlation between AIRI and CDI is relatively constant until the middle of the 20th century, after which the relationship breaks down. This breakdown is especially apparent in the decadal frequency bands (Charles et al., 1997).

4. Discussion

As an integrative measure of rainfall and surface temperature, the $\delta^{18}O$ of corals provides an especially effective means for describing the continuous evolution of monsoon/ocean coupling, well beyond the range of reliable instrumental records. We have shown here that corals from the Indonesian Maritime Continent can be joined with counterparts from the Pacific and Indian oceans to build a picture of basin-wide surface ocean properties. The zonal climate gradients across the tropical Pacific and Indian oceans feature prominently in nearly every discussion of the origin and predictability of interannual climate change. But we use the zonal isotopic gradients in corals, along with several simplying assumptions about the origin of site-specific variability, to make several basic observations of the possible monsoon–ENSO interaction.

The characteristics and correlations of the Bunaken Island coral $\delta^{18}O$ record strongly suggest that it monitors the air–sea interaction associated with Southeast Asian summer monsoon. The coral record exhibits significant biennial variability that is highly coherent with instrumental SST records from the South China Sea. If it is legitimate to take that biennial variability in the region as a reflection of monsoonal processes (e.g. Meehl, 1997; Shen and Lau, 1995), then the temporal evolution of this coral record helps define an important aspect of the monsoon–ENSO interaction.

Comparison of this western Pacific record with the central Pacific coral records suggests that biennial oscillations do not merely replace ENSO, as a direct competition. For example, the middle part of the 20th century was characterized by weaker variability in both the biennial and ENSO frequency bands. Thus, there is little or no evidence that the monsoon acted as a strong pacemaker for interannual variability by imposing its biennial fingerprint across the Pacific. This is not to say that the monsoonal feedback outlined by Kim and Lau (2001), in which monsoonal winds in the western Pacific drive variability in the central Pacific, is unimportant in the real world. Rather, the data merely suggest that monsoon–ENSO interaction over the 20th century was not so simple (nor powerful, perhaps) as to result in a switch between extreme states of pure biennial and ENSO variability.

The coral records provide some hints that the coupling between the western and central Pacific may be important for determining the overall characteristics of interannual variability across the Pacific. While the coherency between the Bunaken coral record and the South China Sea SSTs was always strong, the coherency of this coral record with respect to the rest of the tropics was reduced significantly in the middle of the century, when total interannual variability was weak. To the extent that monsoonal processes were responsible for biennial variability in the western Pacific in the first place, it is therefore conceivable that changes in the timing or intensity of the Southeast Asian monsoon were somehow also responsible for the strength of the zonal correlations.

However, some aspects of the biennial tendency in the central Pacific do not appear to depend strictly on the strength of the variability in the western Pacific. For example, the modulation of the biennial amplitude in the central Pacific probably cannot involve monsoon feedback alone. If that were the case, then one might also expect to find a clear decadal periodicity in the climate records from the western Pacific region. At Bunaken, decadal variability (at periods longer than 10 years) is weak, and the energy in the biennial band was more uniform throughout the 20th century than in the central Pacific. On the other hand, the coral records do not rule out the possibility that the monsoon/ENSO connection lies in the seasonal timing of monsoonal anomalies in the western Pacific, as opposed to the strength of the wind forcing. Although the coral records cannot address this issue directly, they do provide a specific framework for more detailed investigation of the instrumental record.

Observations of the evolution of zonal gradients are also important in the Indian Ocean, because the question of whether the internal dynamics of the basin mediate the interaction between the monsoon and tropical ocean is currently a subject of considerable debate. For example, it has been suggested that Indian Ocean processes might be responsible for the changes in correlation between the South Asian monsoon and the tropical Pacific, among other effects (Chandrasekar and Kitoh, 1998; Webster et al., 1999; Krishnamurthy and Goswami, 2000). The coral records presented here were taken from locations near both poles of the Indian Ocean Dipole. Both records show a very strong correlation to the tropical Pacific on interannual to decadal timescales. Thus, though it may be possible that the Indian Ocean behaves according to its own internal processes – for example, the events of 1997–98 clearly show that internal dynamics are important, and the phase in the decadal band suggests a slightly different time constant for decadal variability than the Pacific – the coral evidence nevertheless demonstrates that, throughout at least the last 100 years, the basic patterns of rainfall and temperature in the Indian Ocean were linked strongly to the zonal excursions of the convective regions in the Pacific.

Our coral-derived assessment of statistical associations differs markedly from previous conclusions concerning the uniqueness of the Indian Ocean Dipole (Saji et al., 1999). Perhaps the difference results from the fact that the $\delta^{18}O$ gradients reflect an integrated measure of rainfall and SST changes, whereas the instrumental dipole index is defined on the basis of temperature alone (though it should be noted that, over the past 20 years, the individual dipole structures of temperature and rainfall overlap each other). Or perhaps the added length of the coral records provides a more representative view of the system, especially for the decadal variability. In any case, our observations tend to support previous suggestions that the coupling between the monsoon indicators in the Indian Ocean and ENSO is strongest when ENSO is strong itself (Kumar et al., 1999). Both of these conclusions are significant for considerations of past and future climate connections across the tropics – for example, modeling studies suggest that the behavior of the western Indian Ocean might be crucial for determining monsoonal rainfall over both Africa and South Asia (e.g. Goddard and Graham, 1999).

There is likewise little support in the corals for an independent link between Southwest Indian monsoon strength and the Indian Ocean Dipole, apart from the common response to ENSO. Over the 20th century, the correlation between the Indian Ocean coral index and Niño 3.4 became strong just at the time when the relationship between the monsoon and ENSO seemed to weaken. Among other implications, this observation suggests that the coupling between the Indian Ocean and the Pacific Ocean cannot be the cause of the evolving monsoon/ENSO relationship. Instead, it is much more likely that the changes in the Asian monsoon/ENSO relationship were the result of mid-latitude processes affecting the monsoon, as opposed to changes in the teleconnections between tropical ocean basins. Similar conclusions were reached through analyses of subtropical ocean/monsoon relationships (Wang et al., 2001).

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