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Coral Reefs

Evaluating climate indices and their geochemical proxies measured in corals

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Abstract. Standard ocean/climate indices such as the Niño-3 sea surface temperature (SST) index, based on sparse instrumental data, and atmospheric indices such as the Southern Oscillation Index (SOI), may now be substituted and/or extended by coral-based indices. Several elements or their isotopes are incorporated in coral aragonitic skeletons at predictable concentrations, some of which are temperature or salinity dependent. The availability of century-old corals, at key oceanographic sites, permits the establishment of a network of proxy climate indices.

Introduction

With very few exceptions, continuously recorded measurements of tropical ocean physical or chemical properties do not exist prior to 1950. Most instrumental records of tropical climate which extend prior to 1950 are atmospheric, not oceanic, time series; ocean temperature time series that do exist may be corrupted by changes in the measurement process, such as the gradual switch from bucket to engine intake water starting around 1940. Thus, with the instrumental records, we do not have enough realizations of the frequently occurring oceanic phenomena, such as El Niño/La Niña, much less lower frequency changes, to adequately characterize the natural variability of the climate system.

The problem of sparse data is exacerbated by the fact that many scientists believe that man has already influenced modern sea surface temperatures through the injection of fossil fuel CO_2 into the atmosphere (Hansen and Lebedeff 1987), as well as perturbed the natural temperature/climate variability, such as the El Niño/La Niña phenomena (Trenberth and Hoar 1996).

In order to extend the tropical ocean/climate records to pre-anthropogenic time, proxy records of climate or ocean properties must be used. Arguably, corals are the most promising tool for this purpose because they incorporate some elements or their isotopes into their carbonate skeletons in predictable concentrations, albeit modified by physiological processes. Corals from many diverse oceanic locations have already proved to be an excellent means by which the modern ocean/climate record can be extended over many centuries (Nozaki et al. 1978; Isdale, 1984; Dunbar et al. 1994; Charles et al. 1997). An additional advantage is that reef sequences spanning millennia allow the reconstruction of climate conditions during times of very different boundary conditions, for example, when the Maritime Continent emerged prior to 11 000 years ago, or when the Earth's seasonal radiation gradients were at their extremes (i.e., the Milankovitch orbital cycles).

There are three dominant and inter-related components of the tropical ocean/climate variability that we are studying using coral-based reconstructions: (1) the El Niño/La Niña Southern Oscillation system; (2) the Asian Monsoon system; and (3) thermal conditions of the "warm pools". None of these components operates in isolation; in fact, there are interesting and complex interactions between all three. Resolving the interactions is critical, because the interannual and interdecadal variations in global rainfall patterns associated with these systems have profound socio-economic consequences. Our objective is to study the many facets of these systems, and in particular their interactions, by first developing an appropriate network of coral-based time series.

The vast array of coral atolls throughout the tropics permits us to take a broad-scale approach to studies of non-stationary ocean/climate phenomena. For example, in the Pacific, Kiritimati and Kanton Atolls are located nearest to the maximum thermal signal associated with the El Niño/La Niña phenomena, while Sulawesi and Tarawa Atoll bracket the regions of greatest rainfall anomalies tied to the Southern Oscillation migration.

It is important to note that our acoustic surveys show drowned coral reefs at all of these key sites, fossil reefs that hold archives of ancient ocean/climate conditions, when physical or climate boundary conditions were very

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different from modern conditions. Chronological resolution and control are always important issues for the development of any long time series. Similar to the composite radiocarbon dendrochronology (tree-ring) record which spans 11 000 years of continuous record, cross-correlation of living and dead corals can be done for many millennia using two methods. First, annual density banding and/or chemical marker cross correlation can be measured much like tree ring cross-dating. Second, the $^{230}Th/^{234}U$ dating method by mass spectrometry can date individual annual bands in a fossil coral to within an uncertainty of $\pm 1\%$ of the actual age, a remarkable analytical achievement developed by Edwards et al. (1987).

Thus, equipped with the appropriate material and methods, we are in a position to measure more fully the evolution of the tropical climate system. Our work in the monsoonal climate regions and in the Pacific "warm pool" regions will be presented elsewhere.

In this work, we use the study of El Niño and the Southern Oscillation to illustrate the use of coral chemical analysis for precise and accurate ocean/climate system reconstructions for the past century. First, we illustrate the need to provide a more accurate and longer index of ENSO by examining the quality, length, and biases of the instrumental record. Second, we show what chemical thermometers have to offer. Third, we outline the requirements for a minimum sampling grid necessary to capture the non-stationary ocean/climate phenomena such as ENSO.

El Niño/Southern Oscillation system

Over the course of an El Niño-Southern Oscillation (ENSO) cycle, the central equatorial Pacific (170°E to 140°W; 5°N to 5°S) experiences extreme fluctuations in sea surface temperature (SST) and rainfall. Differences between warm and cold phase conditions exceed 4 °C and 400 mm/month in precipitation. Anomalous conditions are driven by changes in equatorial upwelling and atmospheric circulation, which bring about zonal extension of the western Pacific warm pool (Picaut et al. 1996) and migration of the Indonesian tropical convective rainfall regime (Bjerknes 1969). It is important to note that shifts in atmospheric heating and moisture content associated with the Indonesian low pressure system are responsible for carrying the ENSO signal to the extratropics (Horel and Wallace 1981).

In the eastern central equatorial Pacific, the predominant surface ocean ENSO signature is an SST anomaly due to changes in wind stress and surface ocean circulation. Normally, SSTs in this region are low relative to the western Pacific, due to equatorial upwelling and eastern boundary current flow westward from the coast of South America. At Kiritimati Island (157.3°W, 2°N), the warm phase of ENSO brings reduced equatorial upwelling and weak easterly winds, allowing the SST to warm by several degrees.

The ENSO warm phase brings anomalous atmospheric convective activity to the western part of the central equatorial Pacific. At Tarawa Atoll (172.9°E, 1.4°N), seasonal and interannual SST fluctuations are usually small (range <1.5 °C) and ENSO is manifest in seasonal rainfall anomalies of 300–400 mm/month (Ropelewski and Halpert 1987). Kanton Island (171.4°W, 2.5°S), 1800 km to the east, experiences both the SST and precipitation effects of ENSO. Therefore, a network of these three sites is required to monitor a non-stationary, quasi-periodic phenomenon such as the atmospheric component of ENSO.

Data and methods

Instrumental data

The Niño-3 index of sea surface temperature anomalies in the eastern equatorial Pacific is commonly used to monitor and predict the oceanographic thermal signature of El Niño/La Niña events. The Niño-3 SST index is the average SST anomaly over the region 150°W-90°W, 5°N-5°S (Climate Analysis Center 1996) (Fig. 1). The Niño-3 SST anomaly (in standard deviation units) is formed by normalizing the averaged data by the 1951–80 seasonal cycle. Here the standard Niño-3 sea surface temperature has been constructed for the 1900–1992 period from GOSTA (Bottomley et al. 1990) SST data (Fig. 1). Although some attention has been focused on data scarcity prior to 1950, there has been much less notice paid to the potential spatial aliasing due to heterogeneous sampling of sea surface temperatures within the Niño-3 region (Fig. 2).

The Southern Oscillation Index (SOI) is a monitor of the atmospheric response to El Niño/La Niña surface ocean conditions. It is the standardized sea level pressure difference between Darwin, Australia and Papeete, Tahiti (Climate Analysis Center 1996) (Fig. 3). The SOI is constructed by first removing the seasonal cycle from each time series and applying instrumental bias corrections. The resulting anomaly series are then normalized by the 1951–80 monthly mean and standard deviations of the data. The time series are differenced and standardized by the 1951–80 mean and standard deviation to produce the SOI.

Stable isotopes

The oxygen isotopic composition of coral aragonite is a function of SST and $\delta^{18}O_{sea\ water}$ (Epstein et al. 1953; Craig and Gordon 1965; Weber and Woodhead 1972) (Fig 4). In the tropical Pacific the $\delta^{18}O$ of precipitation in the convergence zone is approximately $-9‰$ (SMOW), therefore the $\delta^{18}O$ of sea water is strongly dependent on salinity (Fig. 4). In contrast, the strontium/calcium ratio (Sr/Ca) in coralline aragonite is mainly a function of SST (Beck et al. 1992). Sr/Ca and $\delta^{18}O$ measurements on the same samples provide unique temperature and salinity estimates (McCulloch et al. 1994). However, paired measurements for long time series are currently impractical because Sr/Ca measurements require tedious analytical procedures that greatly limit the number of samples that can be run per day (Beck et al. 1992). Instrumentation, such as the Plasma 54, is currently under development and will someday address this need.

High temporal resolution (weekly or monthly) time series of sea surface temperature and/or salinity anomalies may be extracted from the oxygen isotopic composition, because reef corals can maintain extension rates of 5–15 mm/y for centuries. Application of the $\delta^{18}O$ tracer has already yielded century-scale records of sea surface condition anomalies tied to ENSO, from a range of sites spanning the equatorial Pacific (Fig. 5).

In this study, standard analytical procedures were followed to create the Kiritimati, Kanton and Tarawa isotopic records (Shen et al. 1992; Cole et al. 1993; Moore et al. 1997 in preparation; Evans et al. 1997). The Kiritimati and Kanton corals are identified as *Porites* sp. (D. Potts, personal communication) Coral heads were slabbed along the growth axis and X-radiographed for densitometry

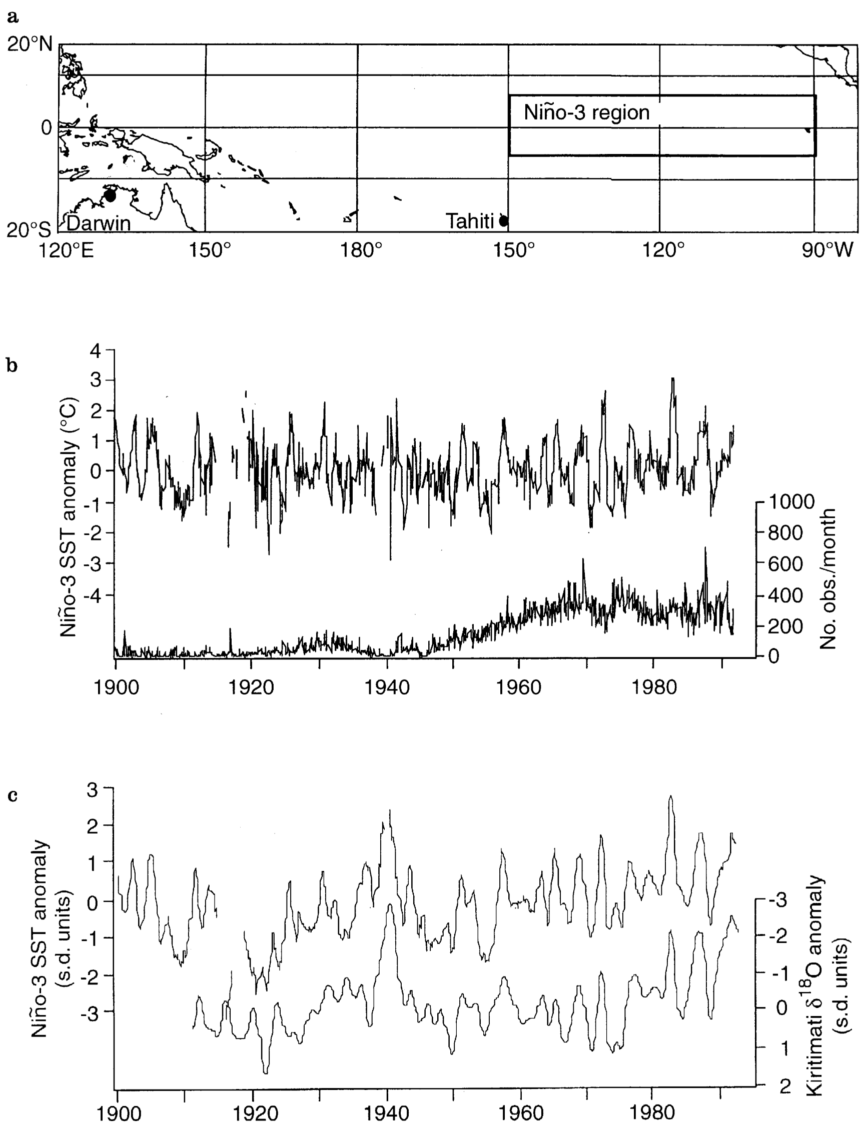

Fig. 1a–c. Construction of the Niño-3 SST anomaly index, and comparison with coral data from Kiritimati. **a** Geographic extent of the Niño-3 box. **b** Niño-3 SST anomaly and number of observations per month (from GOSTA data; Bottomley et al. 1990). **c** Niño-3 SST anomaly compared to the Kiritimati anomaly series, smoothed with a 13-month box filter

study; slabs were then ultrasonically cleaned in distilled deionized water and dried at 50 °C prior to sampling. Samples for oxygen and carbon isotope analyses were drilled from the slabs starting from just below the most recent growth and extending to maximum down core depth. Samples were drilled from lines chosen parallel to the axis of maximum growth. Sequential isotopic analyses were made using a Finnigan MAT-251 mass spectrometer coupled to a Carousel-48 automated sample preparation device. The 1-σ measurement precision is $\pm 0.06‰$ and $\pm 0.04‰$ for $\delta^{18}O$ and $\delta^{13}C$ analyses, based on measurements of an internal lab standard. All measurements are reported relative to the PDB standard. Calendar ages were assigned based on the annual density bands and the annual cyclicity of the $\delta^{13}C$ records (Fairbanks and Dodge 1979). Here the data have been standardized relative to the 1951–80 reference period to match treatment of the instrumental data. The Tarawa isotope record shown here has already been described in detail (Cole et al. 1993). The complete Tarawa record, consisting of two temporally overlapping coral records which have been normalized and spliced together, covers the period 1894–1989 at monthly resolution.

Monthly water samples were collected from a network of coral reef sites in the tropical Pacific and analyzed for salinity and $\delta^{18}O$ (Fig. 4). A regression of $\delta^{18}O$ versus salinity shows a very strong correlation ($r^2 = 0.92$) with the following equation:

$$\delta^{18}O_{\text{sea water}}\ (‰,\ \text{SMOW}) = 0.273(\text{salinity, p.s.u.}) - 9.14‰$$

Analyses were made on a Micromass Multiprep automatic water equilibration and analysis system interfaced to a Micromass Prism III mass spectrometer. External precision is better than $\pm 0.02‰$.

Results

The construction of the Niño-3 SST anomaly and the SOI indices of ENSO variability are shown in Figs. 1 and 3, respectively. Plotted on the same scales are the standardized Tarawa, Kanton and Kiritimati coral isotopic time series. Both the Niño-3 and SOI indices have significant seasonal cycles and instrumental corrections. In addition, the observational frequency in the Niño-3 box decreases markedly before 1950, and both instrumental data series have significant data gaps in the pre-1950 era (Fig. 2).

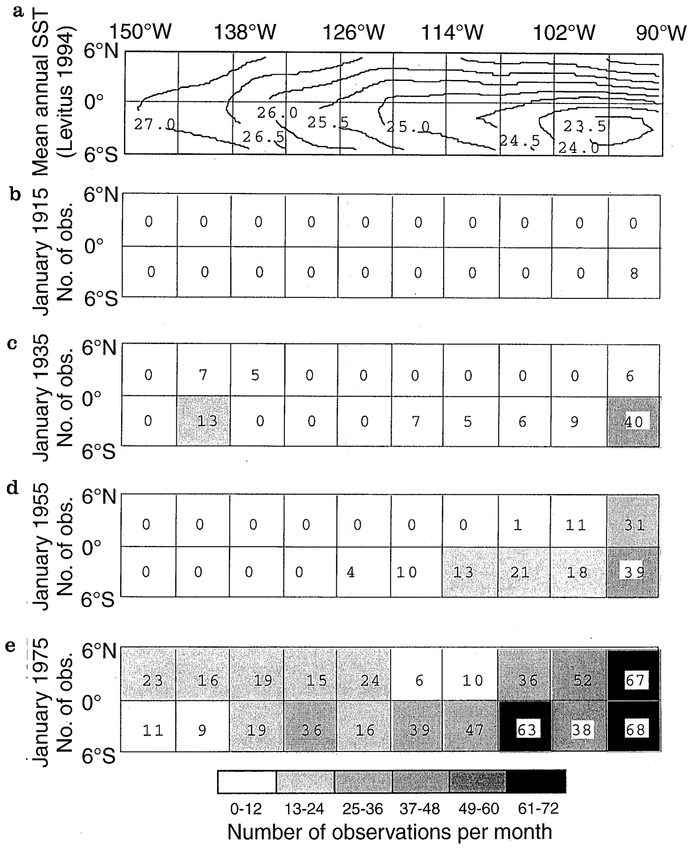

Fig. 2a–e. Observational frequency in the Niño-3 region. **a** Mean annual sea surface temperature (Extended to 6°S–6°N to accomodate data gridded in 2° × 2° boxes, Levitus 1994). **b**, **c**, **d**, **e** Observational frequency for January 1915, January 1935, January 1955, and January 1975, respectively

Figure 2 shows the mean annual SST for the Niño-3 box and the pattern of observational frequency for Niño-3 for four representative periods over the last century. Observational frequency does not reach full coverage until the 1970s. Prior to that, most measurements are in the cooler eastern section.

Discussion

The ideal indices of El Niño and the associated atmospheric convective phenomena have six main characteristics. First, the indices are direct measures of sea surface temperature (El Niño) and precipitation (Southern Oscillation). Second, sampling locations span the complete anomaly field. Third, non-climatic influences are minimal. Fourth, the annual cycle is small compared to the climate anomaly, i.e., a high signal to noise ratio. Fifth, temporal sampling frequency and time series length is sufficient to provide information on frequencies of interest. Sixth, the robustness of the index is testable by construction of independent realizations of itself.

Surprisingly, the two widely used instrumental record-based indices fail to meet the majority of these requirements. The Niño-3 sea surface temperature anomaly index of the ENSO oceanographic signature has well-known flaws (Barnett 1984). The Niño-3 box must be large enough to permit averaging of a sufficient number of observations, especially in the pre-1950 period. However, changes in observational frequency, mode, and location introduce biases into the index. For example, in the 1940s, a transition from shipboard bucket SST to engine intake SST measurement occurred, introducing an estimated warming artifact of $+0.4\,^{\circ}C$ (Barnett 1984). Correcting for this artifact is not simple because it occurred gradually over decades within the Niño-3 box (Jones et al. 1986). Furthermore, time series of observational frequency over the Niño-3 box (Fig. 2) show that observational coverage did not increase in a uniform way. The earliest records for this century are from ship tracks leading to the Panama Canal. Coverage improved as shipping traffic increased, but the critical central/eastern Pacific region was still unobserved. Full coverage of the Niño-3 region was achieved only in the early 1970s.

Together these known potential problems make the study of the behavior of ENSO over the past century difficult, and may overprint real changes in eastern tropical Pacific SST variability. For example, the Niño-3 box straddles two distinct ENSO-affected regions. The beginning of an ENSO warm phase event is marked by SST warming in the eastern part of the Niño-3 box, along the coast of South America. The mature phase of ENSO, several months later, brings maximum SST anomalies to the western portion of the box (Cane 1986; Philander 1990). Thus averaging over the Niño-3 box may obscure true oceanographic features.

The Southern Oscillation Index (CAC 1996) is defined as the standardized difference between sea level pressure

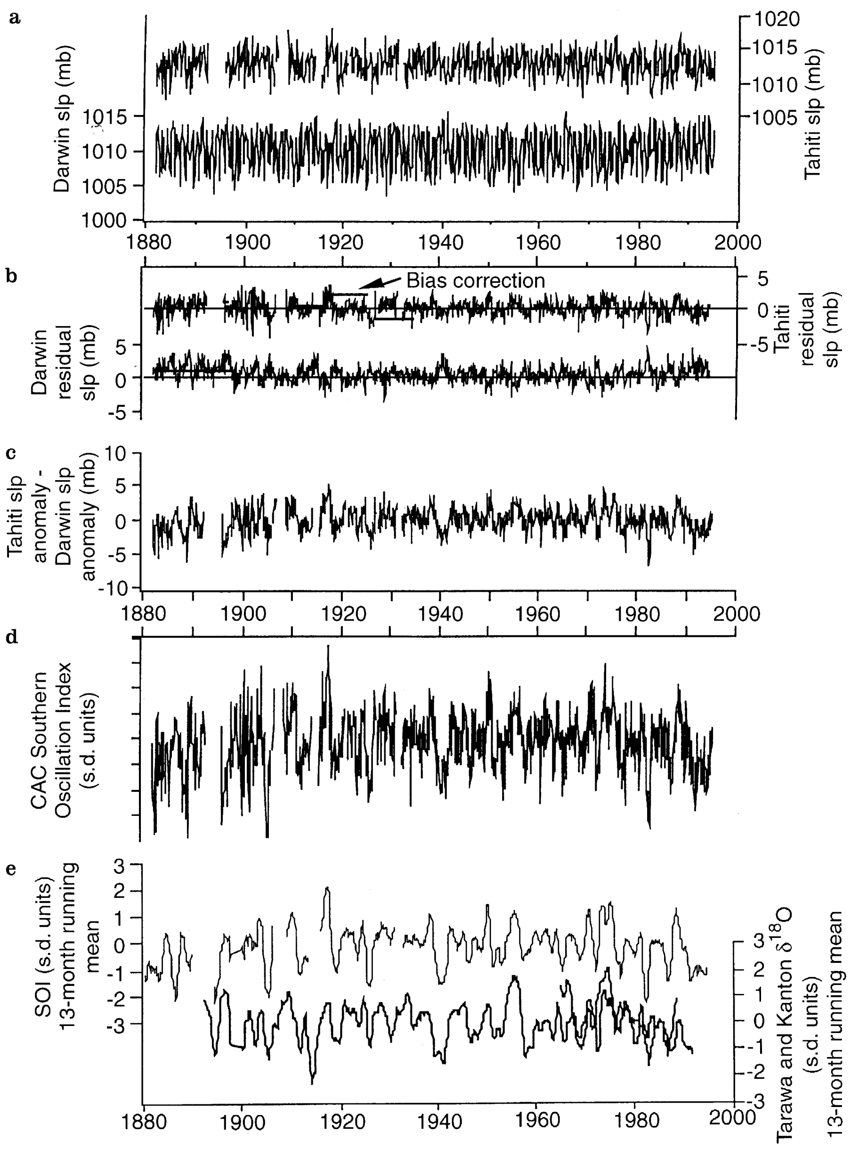

Fig. 3a–e. Construction of the Southern Oscillation Index and comparison with coral data from Tarawa Atoll and Kanton Island. **a** Raw sea level pressure data; **b** sea level pressure anomaly series, before bias corrections; **c** differenced anomaly series; **d** standardized SOI (Climate Analysis Center 1996); **e** SOI (*top curve*) and coral time series (Tarawa record is 1894–1989, Kanton is 1965–1992), smoothed with a 13-month box filter

(SLP) anomalies at two stations, Tahiti and Darwin, Australia, which are located within an interhemispheric and temporally varying pressure oscillation (Figs. 1, 3). In fact, there is evidence that the oscillatory mode described by the SOI extends into the extratropics (Horel and Wallace 1981). Potential biases and frequency aliases may be introduced due to changes in instrumentation and significant data gaps, uncertainty in the application of corrections, and unavailability of substitute data series. The presence of a strong annual SLP cycle at both Darwin and Tahiti makes interannual and lower frequency variability a small fraction of explained variance. These factors conspire to limit the usefulness SOI record prior to 1935 (Trenberth 1984).

Coral-based indices of sea surface and atmospheric conditions overcome many of the obstacles confronting instrumental indices, although they certainly have potential shortcomings of their own. As an example, consider the ENSO monitoring transect based upon Sulawesi, Tarawa, Kanton, Kiritimati and Galàpagos coral records (Fig. 5). The location of Tarawa puts it within the heart of the ENSO precipitation-sensitive region observed by Ropelewski and Halpert (1987; Fig. 5). At Tarawa, Cole et al. (1993) showed that a 96-year, monthly oxygen isotope record captures sea surface salinity fluctuations associated with ENSO. They noted periods during which salinity anomalies in the western-central equatorial Pacific were not matched by temperature anomalies further east, and that the strong 1982–3 warm phase event was only weakly recorded at Tarawa. Our isotopic analysis of a coral collected from Kanton Island, however, shows both the oceanographic and atmospheric signatures of the strong 1982–3 ENSO (Fig. 3). This example illustrates the problem of stationarity and how monitoring non-stationary climatic phenomena at a single location can be misleading. The advantage of studying the central tropical

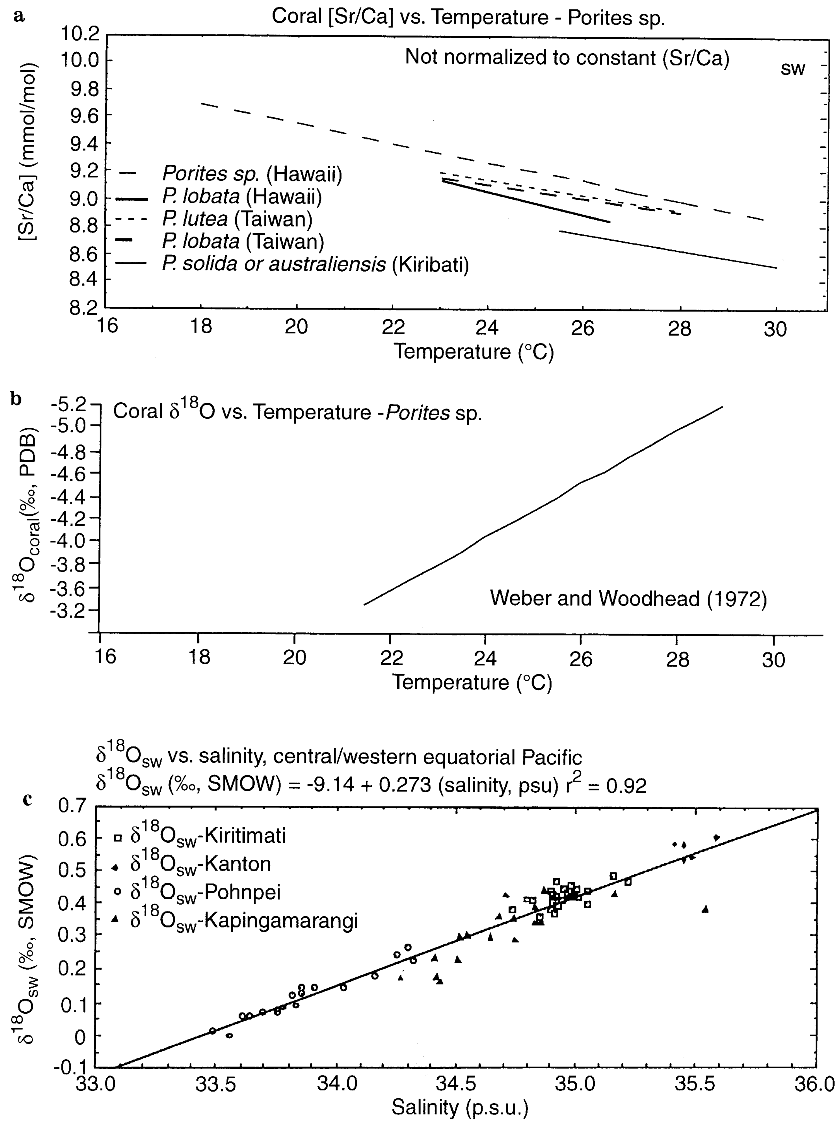

Fig. 4a–c. Tracers of sea surface temperature and salinity. **a** Sr/Ca vs. SST for several species of *Porites* (Schneider and Smith 1982; De Villiers et al. 1994; Shen et al. 1996; Evans et al. submitted 1997. **b** $\delta^{18}O_{coral}$ vs. SST for *Porites* sp. The slope is 0.22‰ $\delta^{18}O$/°C. **c** $\delta^{18}O_{seawater}$ vs. sea surface salinity for the central and western Pacific (data from this work)

Pacific sites, where we find the largest temperature and precipitation (salinity) anomalies, is the fact that the magnitude of the ENSO signal is large relative to the annual cycle (Fig. 6).

An alternative approach is to monitor the departure of the Indonesian Low from its canonical or average position over the Maritime Continent during ENSO events. During every ENSO event, the Indonesian Low migrates eastward and diminished rainfall is observed in the Maritime region. However, since the Maritime Continent has a large annual cycle in precipitation, it is often difficult to measure the ENSO precipitation anomaly (Figs. 5, 6). Even after removal of the annual cycle, the correlation of the $\delta^{18}O$ of Indonesian corals with ENSO indices is much weaker than at central Pacific sites such as Tarawa and Kanton.

Kiritimati, at the eastern edge of the western Pacific warm pool, experiences interannual SST anomalies associated with ENSO up to three times as large as seasonal SST variability. Oxygen isotopic data from Kiritimati and Tarawa corals are better correlated to the instrumental ENSO record than any other proxy time series (Cole et al. 1993; Evans et al. 1997) (Fig. 1). Analogous to the Indonesian and Tarawa monitoring sites, Galàpagos corals always record the ENSO warming but the ENSO signal to annual cycle is relatively small for the Galàpagos region compared to Kiritimati (Fig. 6). Thus, there is clear justification for monitoring ENSO phenomena along an east-west transect from the Galàpagos through the central Pacific to Indonesia (Fig. 5), in order to adequately capture the natural variability of the ENSO system for the past century.

The most important contribution of coral indices of climate may be to extend our knowledge of the climatology of the tropics to periods with different boundary conditions. These data may allow us to elucidate relationships between low frequency tropical climate variability and the global climate, which cannot be resolved by instrumental data.

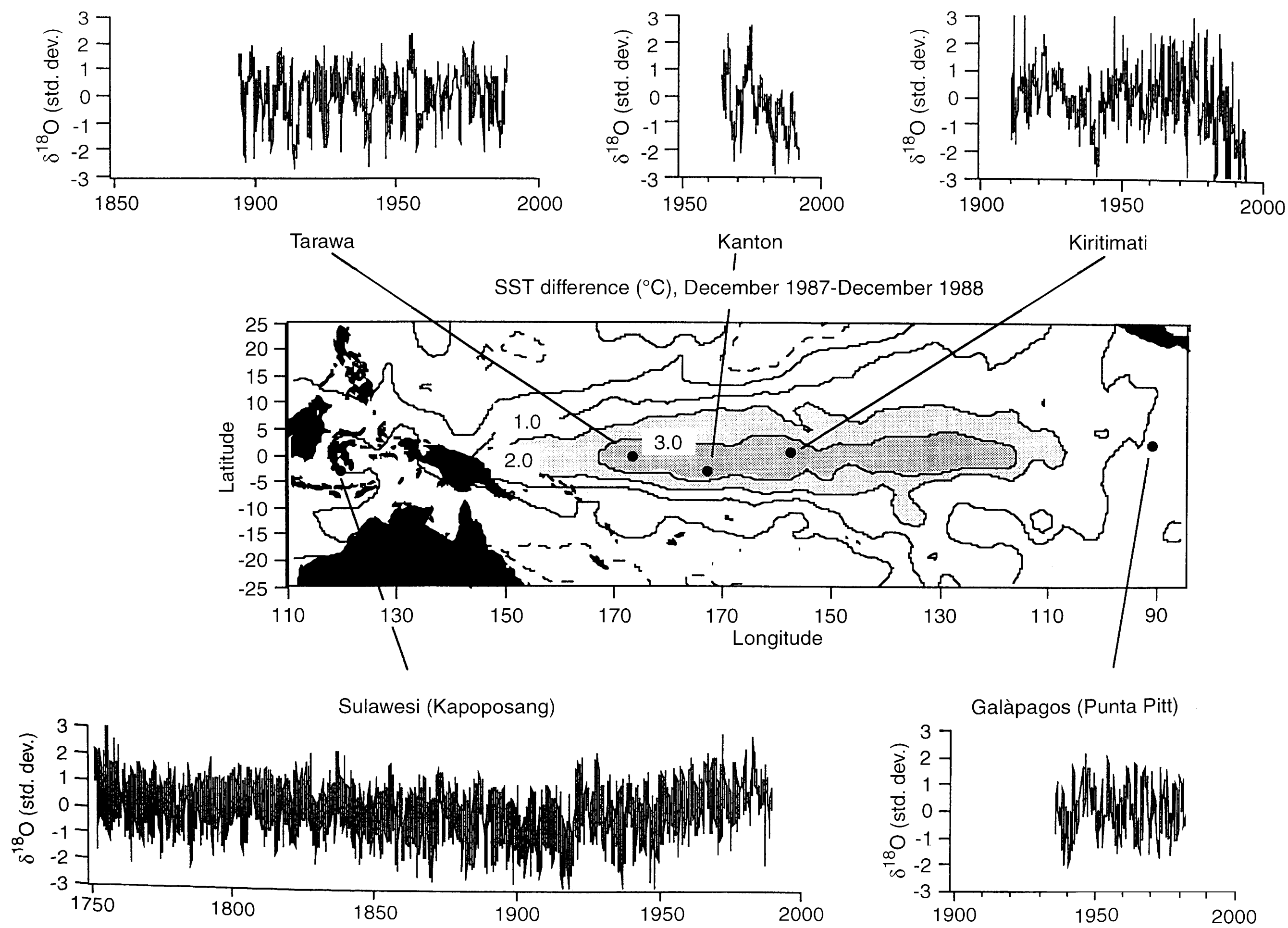

Fig. 5. Coral-based proxy records of ENSO from sites spanning the equatorial Pacific basin (each record is standardized by subtracting its mean and dividing by its standard deviation). Coral data from Cole et al. 1993 (Tarawa), Evans et al. 1997 (Kanton and Kiritimati), Moore et al. 1997 (Sulawesi), and Shen et al., 1992 (Galàpagos). The 1986-7 SST anomaly field (GOSTA data; Bottomley et al. 1990) is *overlain* on the map. Regions with SST anomaly of greater than 3 °C are *shaded*

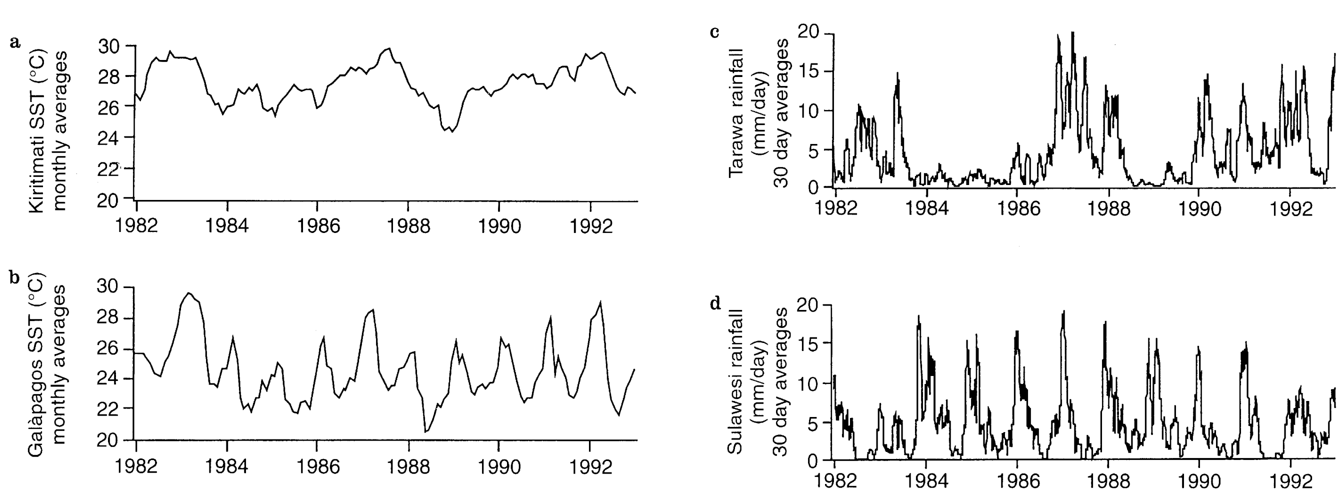

Fig. 6a–d. The seasonal cycle of sea surface temperature and rainfall at four sites spanning the equatorial Pacific. Interannual variations are manifestations of ENSO. **a** SST at Kiritimati; **b** SST at Galàpagos; **c** rainfall at Tarawa; **d** rainfall at Sulawesi. Data from Reynolds and Smith (1994) and Spencer (1993)

Conclusion

The available instrumental climate record contains temporal and spatial inhomogeneities that render it less than ideal for the purposes of studying low frequency features of the modern climate. Massive reef corals have been shown to record features of tropical climate, both atmospheric and oceanographic, in the chemical and isotopic composition of their skeletons, at high temporal and spatial resolution. Coral-based climatic reconstructions provide an alternate, independent means of accurately and precisely testing the instrumental record and extending it to pre-anthropogenic times.

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