



Giant bivalves (*Tridacna gigas*) as recorders of ENSO variability

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ABSTRACT

We compare monthly resolved oxygen isotope records derived from a giant bivalve shell, *Tridacna gigas* and massive *Porites* corals collected along the northern coast of Papua New Guinea. This intercomparison study demonstrates that $\delta^{18}\text{O}$ profiles obtained from these different aragonite-secreting organisms collected from within a 30 km range are correlated in great detail and record the timing and amplitude of seasonal and interannual (ENSO-related) variations in sea surface temperature (SST) and water isotopic composition which is closely related to rainfall. Furthermore, the *T. gigas* record is shown to be close to isotopic equilibrium with the local sea-water, in contrast to the corals which are approximately -4% offset. These results reveal that living and fossil *T. gigas* clam shells have the potential to yield reliable records of past changes in seasonality and ENSO variability, as well as mean climate conditions. In particular, since the non-porous shells are generally more resistant to diagenesis than coral skeletons, they may provide robust estimates of past tropical climate for periods and locations where unaltered corals are absent.

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1. Introduction

The El Niño Southern Oscillation (ENSO) is a naturally-occurring interannual climate oscillation that originates from coupled ocean-atmosphere interactions in the equatorial Pacific (Philander, 1990). It is the largest source of interannual climate variability on Earth, with near worldwide impacts reflected in changes in temperature, rainfall, and the occurrence of extreme events such as floods. Although there have been significant advances in understanding the dynamics of the Pacific Ocean climate variability, the current generation of climate models used for future prediction is not yet able to provide a reliable estimate of the likely response of ENSO to increasing atmospheric CO_2 and the associated global warming (Collins, 2000; Merryfield, 2006). To help understand the sensitivity of ENSO to changes in climate boundary conditions, as well as to reveal the range of unforced variability in the system, past changes in seasonality and ENSO are often reconstructed from natural archives. In particular, it has been shown that the skeletons of annually-banded reef-building corals are useful recorders in this regard e.g. (Cobb et al., 2003; McGregor et al., 2002; Tudhope et al., 2001). Molluscan time series (isotopic and sclerochronological) have been shown to be useful for palaeoclimatic reconstruction (e.g., Chauvaud et al., 2005; Elliot et al., 2003; Jones et al., 1989; Schone and Fiebig, 2009; Weidman et al., 1994; Williams et al., 1982) and have also been used to reconstruct ENSO (Black, 2009; Carre et al., 2005a,

2005b; Lazareth et al., 2006; Rollins et al., 1987; Schone et al., 2007; Thebault et al., 2007) however they are limited in their application as they produce relatively short timeseries (e.g., (Carre et al., 2005a)) or are extra-tropical, away from the centres of action of the ENSO system (e.g., (Schone et al., 2007)). These factors complicate their use for assessing variation in strength and frequency of El Niño events under different boundary conditions. Here we test the potential of giant reef dwelling bivalves from the Western Pacific Warm Pool (WPWP) as an additional tool for such studies.

Massive *Porites* spp. corals and *Tridacna* spp. clams are both reef-dwelling, aragonite secreting organisms that deposit annually-banded skeletons. These annual bands can be subsampled and analysed to derive profiles of oxygen isotope ($\delta^{18}\text{O}$) which have been shown to reflect the combined effects of regional SST and $\delta^{18}\text{O}$ water ($\delta^{18}\text{O}_w$) from which they precipitate their aragonite structures e.g. (Aharon, 1991; Quinn et al., 1998). $\delta^{18}\text{O}$ timeseries in modern and fossil corals collected in northern Papua New Guinea in the heart of the Western Pacific Warm Pool (WPWP) have been used to reconstruct ENSO variability for selected windows of time over the past 130 ka (McGregor et al., 2002; Tudhope et al., 2001). Modern and fossil *Tridacna gigas* have also been studied from the same locality to obtain estimates of past mean climate (Aharon, 1983; Aharon and Chappell, 1983), but to date they have not been used to reconstruct seasonal and interannual, ENSO-related, climate variability. Published records of the massive shells of *Tridacna gigas*, the largest of the *Tridacna* family, rarely extend beyond 60 yrs (Jones et al., 1986; Watanabe et al., 2004) although they are believed to live over 100 yrs (Rosewater, 1965). Living corals can provide up to multi-century-long records that are necessary to study interdecadal climate variations (Linsley et al., 2000; Tudhope et al.,

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2001). Furthermore, use of high-precision U-series dating of sub-fossil corals can be used to generate extended records back into the late Quaternary (Cobb et al., 2003). However due to their porous structure, sub-aerially-exposed fossil corals are often subject to extensive diagenetic alteration e.g. (McGregor and Gagan, 2003). An advantage of *T. gigas* is that they have relatively impervious and finely-layered shells that inhibit infiltration of the meteoric ground waters that may lead to the diagenetic processes of dissolution, recrystallisation and precipitation of secondary calcite (Aharon, 1991). Finally, coral $\delta^{18}\text{O}$ show an isotopic disequilibrium, also called vital effects, which varies between coral species (McConnaughey, 1989; Wellington et al., 1996) whereas available data suggests that *T. gigas* precipitate their shells close to isotopic equilibrium providing the possibility to quantify more accurately past changes in absolute SST and $\delta^{18}\text{O}_w$ (Aharon, 1983; Aharon and Chappell, 1986; Watanabe and Oba, 1999).

Here we investigate the potential to use *T. gigas* $\delta^{18}\text{O}$ profiles as palaeoclimatic archives and in particular as proxies for ENSO variability. Multiproxy approaches are commonly used to increase the robustness of the palaeoclimate reconstructions. An initial validation step is to test these proxies one against the other over a time interval where climate conditions are known from instrumental data. We have obtained a high-resolution $\delta^{18}\text{O}$ profile from a modern *T. gigas* which we first compare to 2 modern *Porites* corals $\delta^{18}\text{O}$ profiles, all sampled within 30 km of each other. Secondly, we compare the *T. gigas* $\delta^{18}\text{O}$ profile with regional records of SST, rainfall patterns and ENSO index.

2. Methods

Samples of *T. gigas* (MT03-7) and *Porites* (H95-64 and H01-9) have been collected from 3 localities along the Huon Peninsula in northern Papua New Guinea (Fig. 1). A whole shell of *T. gigas* (MT03-7) was extracted live in 2002 by local inhabitants from shallow waters at a water depth of around 2.5 m near Kanzarua. Cores H95-64 and H01-9 were sampled from live *Porites* colonies near Sialum Lagoon (Tudhope et al., 2001) and Loto Beach respectively (Fig. 1). H95-64 was sampled from ~2.5 m below mean low water spring tide level behind the barrier reef, adjacent to a well-flushed pass to the open ocean (Tudhope et al., 2001) and H01-9 was collected from ~3 m water depth on a narrow, well-flushed seaward-facing fringing reef.

Profiles of $\delta^{18}\text{O}$ have been obtained by subsampling the annual growth bands. Since the corals grow at ~14–19 mm/yr over their lifespan, we used a conventional slow-speed milling device to sample into continuous 1 mm growth increments to yield better-than monthly temporal resolution. The clam shell $\delta^{18}\text{O}$ record was derived from the inner layer region (behind the pallial line) where growth rates typically reduce from 5 to 10 mm/yr during the juvenile phase of growth to only a few mm per year during adulthood (Aharon, 1991). As previous studies have shown, it is appropriate to sample the inner layer as a continuous record preserving daily growth bands can be observed (Watanabe et al., 2004; Watanabe and Oba, 1999). We used a high precision microdrill to sample the *T. gigas* shell with resolution around 0.2 mm to obtain a similar temporal resolution to the corals. A total of 3 thin sections, of 4–5 cm, long were subsampled for micromilling (Fig. 2).

Powdered aragonite samples were analysed in the Wolfson Stable Isotope Laboratory at University of Edinburgh using a Thermo Electron Delta + Advantage stable isotope ratio mass spectrometer with Kiel Carbonate III preparation device (clam samples at 0.03–0.2 mg), and using a PRISM III stable isotope mass spectrometer with automatic common acid bath sample preparation system (coral samples 0.1–0.3 mg). The standard deviation for a laboratory standard marble powder (MAB2B) run as a sample between December 2003 and January 2006, was $\pm 0.06\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$. All isotopic values are quoted relative to VPDB.

Like corals and many other bivalves, *Tridacna* sp. display variations in shell density on annual timescales (Bonham, 1965) which can be observed as variations in light attenuation (Patzold et al., 1991). The banding of *T. gigas* is thought to vary in concert with seasonal variation in temperature based upon the correlation between more transparent bands (larger crystal size) and more negative $\delta^{18}\text{O}$ of shell carbonate (Elliot et al., 2009; Patzold et al., 1991). In *T. gigas* from the Huon Peninsula, this banding was subtle, presumably because of the low annual amplitude in temperature or other environmental factors. Investigations were made of growth patterns using staining agents such as Mutvei's solution (Schone et al., 2005) and SEM imagery. SEM in particular allows such detail as daily banding to be seen in *Tridacna* sp. Annual growth marks were not made any clearer with Mutvei's solution, implying very low concentrations of polysaccharides and other organic material. Annual banding is observed most easily by preparing a 7 mm thick slab of shell perpendicular to the axial plane and placing this

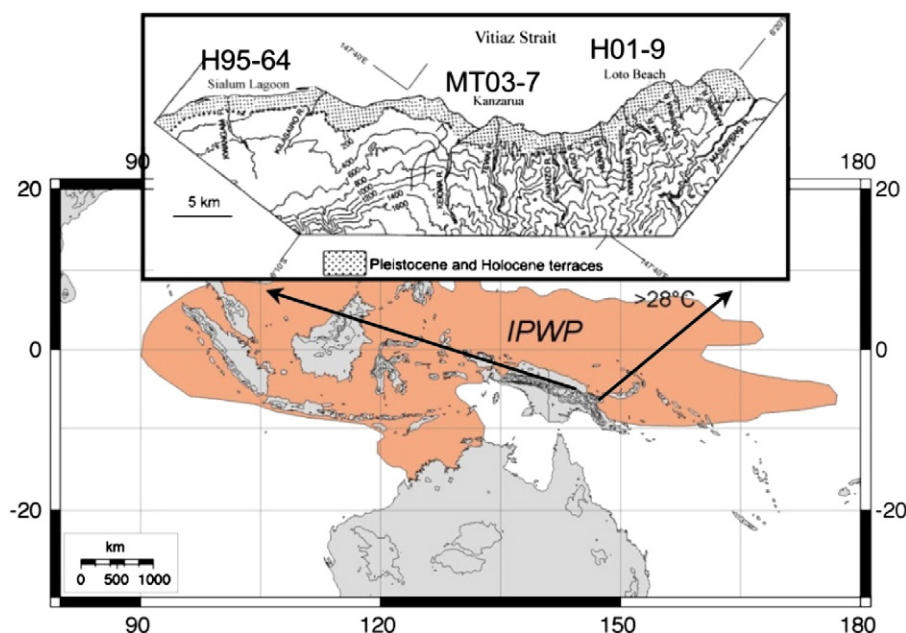


Fig. 1. Map of study area with locations of coral and bivalve sampling. *Porites* (H01-9 and H95-64) and *Tridacna gigas* (MT03-7) samples.

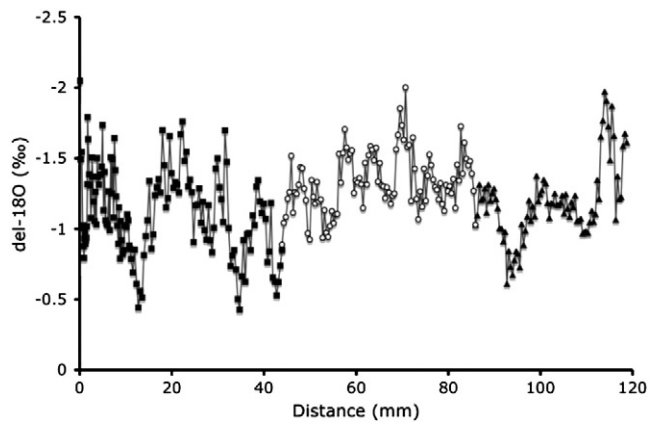


Fig. 2. *T. gigas* (MT03-7) $\delta^{18}\text{O}$ data collected live at Kanzarua. Symbols highlight the successive 3 thin sections that were sampled on this shell. All data is indicated as a function of shell distance, the direction of growth is from right to left.

on a light table. A digital image was then made and the contrast enhanced to show annual banding. The centre of the least dense or most transparent part of the annual band was identified and assumed to be produced during the warmest month (January). This technique was used to assign a basic chronology to stable isotopic results from *T. gigas*. Whilst the alternating light and dark bands on the shell give a good guide to chronology, their subtle meant that it was also necessary to use stable isotopic maxima and minima to position the warmest and coolest months following the same technique used for the coral records (Tudhope et al., 1995, 2001). Age models for coral records were also determined using the date of sampling and a combination of annual growth indicators and isotopic maximum and minima following a similar approach. The timeseries generated (Fig. 3) were not “tuned” to each other, however the use of isotopic maxima and minima will result in some artificial correlation at the monthly, but not the interannual level.

Growth rates can be estimated from the obtained age models. *T. gigas* growth during the juvenile phase is around 16 mm/yr, and around 2 mm/yr during the adult phase, similar to published values (Aharon, 1991). Temporal resolutions for *T. gigas* thus varied from weekly during the juvenile phase to monthly during adulthood considering an average sampling resolution of 0.2 mm. Calculated growth rates for the corals are on average 14 mm/yr for H95-64 and 19 mm/yr for H01-9, and therefore the 1 mm sampling resolution yielded slightly better than monthly resolution throughout. The *T. gigas* (MT03-7) $\delta^{18}\text{O}$ profile covers the period 1986–2002 whereas the *Porites* $\delta^{18}\text{O}$ records cover the periods 1977–1995 (H95-64) and 1987–2001 (H01-9) (Fig. 3).

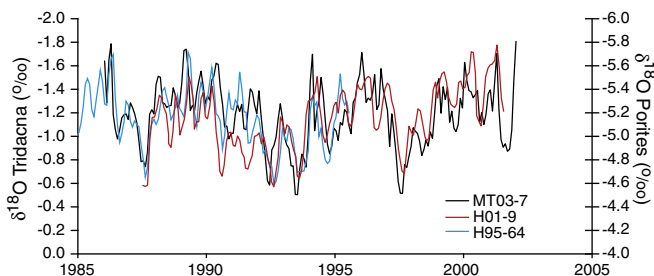


Fig. 3. Comparison of the $\delta^{18}\text{O}$ profiles derived for *Porites* (H01-9 and H95-64) on right axis and *T. gigas* (MT7-i) on left axis. Both y-axis are inverted and the coral y-axis is offset by 4‰ compared to the bivalve y-axis. All profiles have been resampled with monthly resolutions. Correlation coefficient between mean annual values in the coral records is 0.57. The correlation coefficient between the *T. gigas* timeseries and coral timeseries is 0.63 and 0.92 for H01-9 and H95-64 respectively.

Average $\delta^{18}\text{O}$ for MT03-7 is -1.2‰ with a range of -1.9 to -0.5‰ whereas the average $\delta^{18}\text{O}$ for both H95-64 and H01-9 is -5.1‰ with a range of -5.7 to -4.5‰ (Fig. 3). In order to better compare the coral and clam records and to calculate the average offset between the profiles we used linear interpolation to resample each time series into the same (monthly) resolution using the Anlyseries programme (Paillard et al., 1996). For the period where the two coral records overlap, the average monthly offset between skeletal $\delta^{18}\text{O}$ values is 0.06‰ which well within the analytical precision of the $\delta^{18}\text{O}$ measurements. However, there is an average $\delta^{18}\text{O}$ offset between *T. gigas* (MT03-7) and the *Porites* samples of $\sim 4\text{‰}$ (Fig. 3). Specifically, MT03-7–H95-64 yielded an offset of 3.95‰ and MT03-7–H01-9 an offset of 3.97‰.

3. Intercomparison of *T. gigas* and *Porites* sp. isotopic records and instrumental data

3.1. Isotopic equilibrium

Average SSTs at the Huon Peninsula are around 29 °C with an annual range of 0.5 – 1.5 °C in monthly means. Water samples collected in 1977 in Sialum Lagoon have average $\delta^{18}\text{O}_{\text{w}}$ around $0.2 \pm 0.1\text{‰}$ ($n=9$) (Aharon and Chappell, 1986). Using these values and the palaeotemperature equation derived for molluscs $T = 21.8 - 4.69 (\delta^{18}\text{O} - \delta^{18}\text{O}_{\text{w}})$ (Grossman and Ku, 1986), were $\delta^{18}\text{O}_{\text{w}}$ is corrected by -0.27 for conversion SMOW to VPDB (Hut, 1987). The predicted equilibrium skeletal annual average $\delta^{18}\text{O}$ is -1.6‰ . In this region, there are significant seasonal and interannual variations in isotopically depleted (~ -7 to -8‰) rainfall (Rozanski et al., 1993), which translate to changes in surface ocean oxygen isotopic composition ($\delta^{18}\text{O}_{\text{w}}$). To assess how close to equilibrium the skeletons are we ideally need to compare values for the same year and the same month i.e., October 1977 when the water measurements were made (Aharon and Chappell, 1986). Only one of the records (coral H95-64) extends to October 1977, and for that month the $\delta^{18}\text{O}$ value is -4.99‰ , i.e., $\sim -3.85\text{‰}$ offset from equilibrium. Using this, and the mean offset between the clam and H95-64, yields an estimated offset between the clam and seawater of only 0.1‰ $\delta^{18}\text{O}$, which is well within the accumulated uncertainty of equilibrium values. Therefore, our results confirm that *T. gigas* precipitate their shell close to isotopic equilibrium as has been shown previously (Aharon and Chappell, 1986; Watanabe and Oba, 1999).

3.2. Comparison of *T. gigas* and *Porites* profiles

The most striking feature, once the $\delta^{18}\text{O}$ coral data is corrected for a constant $\sim 4\text{‰}$ offset, is the high degree of resemblance between the coral and bivalve records (Fig. 3). Profiles correlate in detail on seasonal and on interannual level and there are no changes in offset between clam and coral through the length of the records. For example, there are 3 well-defined seasonal cycles between 1997 and 2003 and there are clear $\delta^{18}\text{O}$ minima at 1987, 1992, 1993 and 1997 (Fig. 3). A Pearson product-moment correlation for monthly values over the periods where the timeseries overlap was calculated between both the *Porites* and the *Porites* and *T. gigas*. These are calculated as 0.60, 0.59 and 0.51 between the timeseries H01-9 and H95-64, H95-64 and M03-7 and H01-9 and M03-7 respectively. Therefore we observe a very similar correlation between the coral timeseries and each coral and the *Tridacna* timeseries. It is worth noting that because the isotopic signal was used in addition to growth markers to develop the chronology, this will strengthen correlations at monthly resolution. A better representation of the correlation between the records may therefore be given by investigating correlation of annual mean values. The correlation coefficient between the annual mean values in the coral records is 0.57. The correlation coefficient between the *T. gigas* timeseries and coral timeseries is 0.63 ($n=14$) and 0.92 ($n=9$) for H01-9 and H95-64 respectively. In this case the correlation is as good as or better than the correlation at the

monthly level. This is likely to be because the interannual variability in $\delta^{18}\text{O}$ is at least as important as the seasonal variability. In the case of the *Tridacna* and H95-64, this exceptionally good correlation is a product of the coincidence of several strong ENSO events within the years of overlap.

This correlation is particularly excellent given that palaeoclimate archives obtained in coastal areas can potentially reflect micro-environmental hydrography rather than large-scale regional patterns as strong temperature and salinity gradients commonly characterise these areas. However, the three samples reported here were all collected from well-flushed areas subject to strong tidal and wind driven currents and in locations well removed from local riverine influences, i.e. they all grew in water representative of the adjacent ocean. This has been confirmed through use of temperature loggers left in situ for 2 yrs adjacent to coral H95-64 (Fig. 4) which confirm the strong correlation between logger SST variations and ship and satellite derived SSTs for adjacent ocean grid boxes. The excellent reproducibility of coral and clam records illustrates the strength of using these archives to reconstruct large scale hydrographic changes in this area.

Differences in growth rates could also have translated into isotopic offsets between bivalve and coral $\delta^{18}\text{O}$ profiles. Corals at Huon Peninsula are shown to have relatively constant growth rates through this time period (remaining close to 14 mm/yr for H95-64 and 19 mm/yr for H01-9) whereas bivalve shell growth rates reduce from 16 mm/yr during the juvenile phase of growth to 2 mm/yr during adulthood. In many previous studies of bivalves attenuation of growth in later stages of ontogeny combined with lower sampling resolution has meant that the $\delta^{18}\text{O}$ profiles do not resolve the full range of seasonal amplitudes (Aharon, 1991; Goodwin et al., 2003; Jones et al., 1986). For example, (Aharon (1991)) showed that the ontogenic reduction growth patterns in *T. gigas* caused the isotopic record to become attenuated which we do not observe here. Our findings support recent work on the same species showing that given a sufficient resolution there is no attenuation of the seasonal signal throughout the life of the bivalve (Watanabe et al., 2004). Some studies have indicated that tropical bivalves are more likely to grow year round whereas bivalves growing at higher latitudes may have interrupted growth patterns, particularly in winter (Elliot et al., 2003). Extreme summer temperatures can, however, cause growth to reduce or cease as observed in some lagoonal specimens (Romanek and Grossman, 1989). Whilst it is possible that there may be minor interruptions to valve accretion because of biological or environmental variability, the results presented here indicate that the bivalve

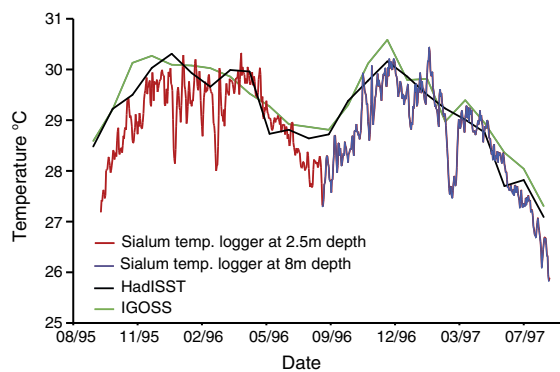


Fig. 4. Temperature loggers placed behind the Lagoon Barrier at 2.5 m below Mean Low Water Springs (MLWS) (red line: 13/09/95–12/08/97) and at the base of the fringing reef opposite the lagoon entrance, 8 m below MLWS (blue line, 25/08/96–12/08/97) in Sialum Lagoon. SST record derived from HadISST and IGOSS data sets for the degree square centred on 147.5°E, 6.5°S. Correlation coefficient between Loggers over period 25/08/96–12/08/97 is 0.97. (NB temperature logger at 2.5 m spans both years, but 1997 results are identical to 8 m temperature logger).

experiences no major growth breaks that would inhibit its ability to resolve the seasonal record is at least as well as *Porites* timeseries.

In summary, the good correlation between $\delta^{18}\text{O}$ coral and bivalve profiles remains constant over the studied period although measurements have been obtained from different carbonate secreting organisms, collected within a 30 km range, in different environmental settings. More importantly, bivalves and corals have fundamentally different biological controls on carbonate formation and different growth rates. The high degree of reproducibility between the coral and bivalve $\delta^{18}\text{O}$ profiles presented here thus shows that at Huon Peninsula, variations through time are relatively unaffected by biological factors such as variations in rates of growth or growth breaks.

4. *T. gigas* a recorder of ENSO variability

In northern Papua New Guinea there is a coupling between precipitation and temperatures on a seasonal and inter-annual basis (Tudhope et al., 1995). El Niño periods are associated with lower than average SST and drier conditions whereas La Niña periods are associated with higher than average SST and wetter conditions (Fig. 5). The changes in $\delta^{18}\text{O}_{\text{w}}$ and SST will thus have similar effects on shell $\delta^{18}\text{O}$ which will become more positive during El Niño and more negative during La Niña phases. The comparison of rainfall and SST anomalies and ENSO index with the *T. gigas* $\delta^{18}\text{O}$ record shows that each El Niño event is recorded in the shell profile by isotopic shifts of around 1 to 1.2‰ towards more positive values (Fig. 5). The *Tridacna* and coral isotopic records display a weak seasonality averaging, 0.2–0.4‰ range in monthly means, and marked interannual events of between 0.3 and 0.5‰ amplitude. The seasonality in skeletal $\delta^{18}\text{O}$ is consistent with the combined effects of a cool and dry season, resulting in isotopically heavy skeleton, and a wet and warm season, resulting in isotopically light skeleton, with temperature contributing about 50% of the range and water composition (via rainfall) the other 50% (e.g., (Tudhope et al., 1995)). Likewise, the interannual variations reflect the combined influence of temperature and rainfall. During the El Niño phase of the Southern Oscillation, this region experiences relative drought as well as slightly reduced SSTs (~ -0.2 to -0.5 °C anomaly). These factors combine to drive skeletal $\delta^{18}\text{O}$ to heavy values, with SST explaining about 30–50% (depending on event) of the skeletal $\delta^{18}\text{O}$ range.

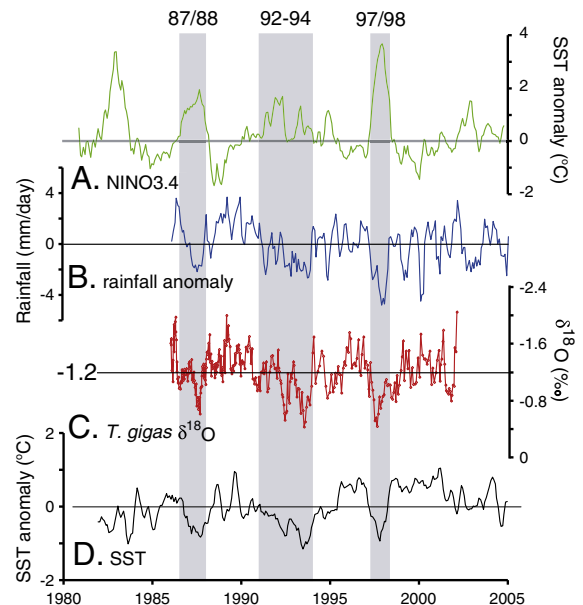


Fig. 5. Comparison of *T. gigas* $\delta^{18}\text{O}$ profile with ENSO and local temperature and rainfall data. A: NINO3 index, B: monthly rainfall anomaly (mm/day), 3pt smoothed data from NASA/GPCPV2 for 146.25°E, 6.25°S, C: *T. gigas* $\delta^{18}\text{O}$ record, and D: SST monthly anomaly, 3pt smoothed data is taken from IGOSS data set for the same grid box as the rainfall data.

5. Conclusions

The *T. gigas* profile for the period 1986 to 2003 thus shows all the major El Niño events that have punctuated this period of time illustrating the usefulness of this archive to reconstruct past seasonality and ENSO variability in this area. *T. gigas* have been shown to be able to produce multi-decadal climatic records, which are required to investigate changes to the frequency and strength of ENSO events in the past. The ontogenic reduction in growth of *T. gigas* does not reduce the reliability with which temperature and $\delta^{18}\text{O}_w$ variability can be reconstructed. This paper validates the use of fossil *T. gigas* $\delta^{18}\text{O}$ profiles in palaeoenvironmental studies.

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