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Interdecadal climate variability in the Coral Sea since 1708 A.D.

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Abstract

Low resolution (5-year) Sr/Ca and $\delta^{18}O$ samples, extending back to 1708 A.D., were analysed from a *Porites* coral core collected from Flinders Reef, an offshore reef on the Queensland Plateau in the western Coral Sea (17.5° S, 148.3° E). Using the Sr/Ca ratio as a proxy for sea surface temperature (SST), we deconvolved a salinity record by subtracting the SST signal from the $\delta^{18}O$ record. Decadal variability in the reconstructed salinity record is closely paralleled by changes in SST, with cooler (warmer) temperatures recorded during wetter (drier) periods. This relationship differs from the conventional view often described for tropical areas, where warm temperatures are associated with wet periods and cool temperatures with dry periods. The anti-correlation between reconstructed SST and salinity observed at Flinders Reef, however, matches the climatic effects expected from variations in the Interdecadal Pacific Oscillation (IPO), a recurrent pattern of SST variability over the Pacific Ocean which is known to modulate Australia's climate, in particular the impact of ENSO events on decadal time scales. On longer timescales, salinity seems to have remained almost constant for the last two centuries after a progressive freshening of surface waters that culminated around 1800 A.D. Conversely, SSTs show a warming trend towards the late 20th century.

Keywords: Coral proxies; Interdecadal variability; Salinity; South Pacific; Coral Sea; Interdecadal Pacific Oscillation

1. Introduction

El Niño-Southern Oscillation (ENSO) variability dominates the climate of the Pacific Ocean on interannual time scales. On longer time scales, there is increasing evidence of the Interdecadal Pacific Oscillation (IPO) driving sea surface temperature (SST) and circulation anomalies over the Pacific region with spatial patterns and climatic conditions similar to those developed during individual ENSO events (Zhang et al., 1997; Folland et al., 1999; Power et al., 1999). The IPO changes phase every 15 to 30 years and is equivalent to the Pacific Decadal Oscillation previously described for the North Pacific (Mantua et al., 1997). This oscillation has been shown to modulate the strength and frequency of ENSO events (Salinger et al., 2001; Mantua and Hare, 2002) and, more importantly, the magnitude of the impact of individual ENSO events (Gershunov and Barnett, 1998; McCabe and Dettinger, 1999; Power

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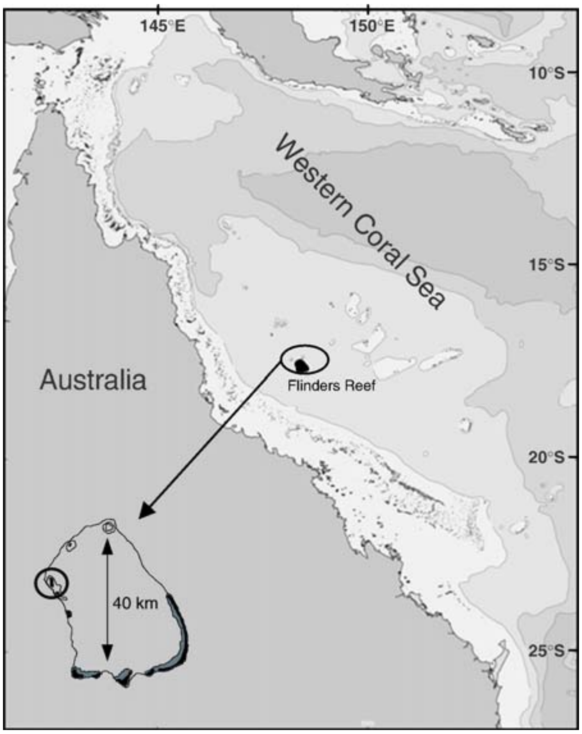

Fig. 1. Map of the western Coral Sea showing the location of Flinders Reef, an offshore reef on the Queensland Plateau (17.5° S, 148.3° E). Sketch shows the location of the coral core and dimensions of Flinders Reef. The coral core was drilled on the northwestern side of the reef (black circle).

et al., 1999). Power et al. (1999), for example, showed a strong IPO modulation of ENSO impacts on Australia's climate. These authors found that during a negative IPO phase, when the tropical Pacific is cooler than average (La Niña-like state), teleconnections between ENSO events and Australia's rainfall are strong, which translates into increased precipitation variability over eastern Australia. Conversely, during warm IPO phases such as those developed during 1924–43 and 1979–97, ENSO teleconnections were weak and Australia experienced reduced interannual rainfall variability (Lough, 1991; Allan et al., 1996; Latif et al., 1997; Power et al., 1999; Hendy et al., 2003). Such interdecadal modulation of the impact of ENSO on Australia's climate has important implications for management policies focused on flood and drought risk (Kiem et al., 2003; Kiem and Franks, 2004).

In this study, we present Sr/Ca and δ^{18}O measurements from a long coral core from Flinders Reef, off northeast Australia. Parallel Sr/Ca and δ^{18}O measurements allow reconstruction of past changes in both SST and salinity over the last 280 years and provide new insights into the influence and dynamics of decadal and longer-term trends of Pacific climate variability. Since the main priority of this study was decadal and longer-term climate variability, we chose a low-resolution sampling, bulk 5-year intervals, instead of the more common annual or sub-annual resolution often presented for coral records. This sampling approach was successfully applied in a compilation of eight coral records from several reefs in the central inshore to midshelf Great Barrier Reef (GBR: Hendy et al., 2002). The location of Flinders Reef, an offshore

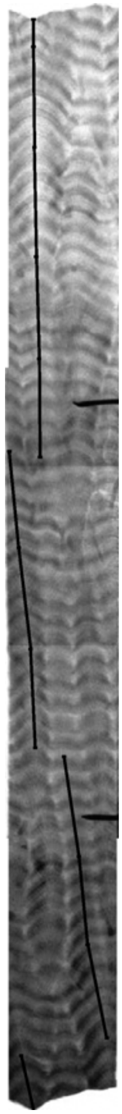

Fig. 2. X-radiograph positive image of annual density banding in Flinders Reef coral core. Couplets of high skeletal density (dark bands) and low skeletal density (light bands) represent one annual growth increment. Black lines indicate positions of 5 year-increment sampling transects which started and finished in the annual low density bands.

reef located far from land influence, is ideal to compare with the extensive work of Hendy et al. (2002) on corals closer to land. The new records are also compared with other century-long coral records from the southwest Pacific.

2. Analytical methods

In May 1992, a long core from a *Porites* sp. coral head was collected from Flinders Reef, an offshore reef on the Queensland Plateau (17.5° S, 148.3° E), 250 km from the north-east coast of Australia and one of the largest discrete reef systems in the Coral Sea (Fig. 1). The coral core was cut lengthwise into 7 mm thick slices and X-rayed to reveal regular and well-defined annual density bands, which were used to establish the coral chronology (Fig. 2). Samples were collected in 5-year intervals along the main growth axis using a 2 mm diameter tungsten carbide bit. This low-resolution sampling, instead of the more common annual or seasonal resolution, was adequate for the purposes of this study, which mainly focuses on long-term changes and multidecadal scales. The pent-annual sampling approach has been applied previously on corals from the GBR, and allows reconstruction of decadal-to-centennial climate variability (Hendy, 2003). It also reduces the error introduced by under or oversampling one or two months of coral material when working with smaller bulk samples. Two short sections from the top and the bottom of the coral core were also sampled every 1 mm following Gagan et al. (1994), providing monthly resolution for the 1735–1737 period (annual extension rate of 12 mm yr^{-1}) and slightly higher resolution for the period 1986–1988, when the annual extension rate was about 16 mm yr^{-1}. For the younger section, the chronology was established by correlating the highest (lowest) monthly Sea Surface Temperature (SST) value (data derived from HadlSST1.1 data set; Rayner et al., 2003) to the lowest (highest) Sr/Ca value. For the 1735–37 period, we took January as the warmest month and assigned the lowest Sr/Ca value to this month.

Stable isotope measurements were performed on a Finnigan MAT 251 with a Kiel carbonate device using 103% phosphoric acid at 90 °C. Isotope data were normalised to the Vienna Peedee Belemnite (V-PDB) using the NBS-19 standard ($\delta^{18}O = -2.20$‰ and $\delta^{13}C = +1.95$‰). Multiple measurements of this standard gave a standard deviation of 0.02‰ for $\delta^{18}O$ and 0.03‰ for $\delta^{13}C$. The same standard deviations were obtained when running duplicate analyses of some of the coral samples ($n = 10$).

Sr/Ca analyses were carried out on a Finnigan MAT 261 Thermal Ionisation Mass Spectrometer by isotope dilution using a ^{43}Ca–^{84}Sr mixed spike. Mass fractionation correction was made relative to natural $^{42}Ca/^{44}Ca = 0.31221$ and $^{86}Sr/^{88}Sr = 0.1194$ using an exponential law. Replicate analyses of a coral standard solution showed excellent reproducibility with a standard deviation of only 0.02% ($n = 11$). See Marshall and McCulloch (2002) for a more detailed description of the methodology.

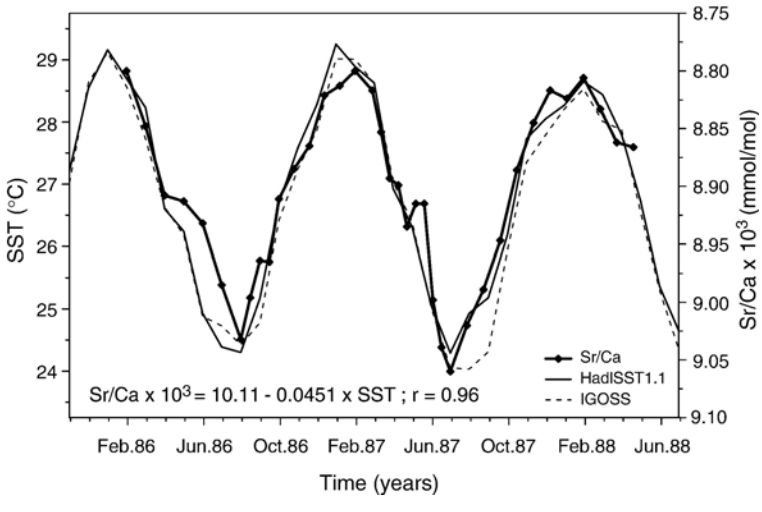

Fig. 3. Monthly Flinders Reef coral Sr/Ca (thick line), monthly SST from HadlSST1.1 (thin line; Rayner et al., 2003) and monthly SST from the IGOSS dataset (dashed line; Reynolds and Smith, 1994) for the period 1986 to 1988. The instrumental SST data are for the 1° latitude by longitude box centered on 17.5 °S, 148.5° E. The equation defines the linear least-squares regression for coral Sr/Ca and SST from HadlSST1.1.

3. Results and discussion

3.1. Sr/Ca–SST calibration and high resolution data

In order to convert the 5-year Sr/Ca measurements to SST, we measured Sr/Ca ratios every 1 mm for the 1986–88 period and fitted the record to monthly SSTs derived from HadlSST1.1 data set (1° latitude by longitude box centered on 17.5° S, 148.5° E; Rayner et al., 2003; Fig. 3). The derived relationship between Sr/Ca and SST obtained by a linear least-square regression was:

$$\mathrm{Sr/Ca} \times 10^3 = 10.11 - 0.0451 \times \mathrm{SST} \quad r = 0.96$$

The fit between the two records was good, although the intercept and slope values were slightly different to previous calibrations published for this area. Despite the differences, SSTs obtained using the Flinders calibration compare well with those obtained from the mean of four previously published Sr/Ca-SST calibrations using *Porites* corals from the GBR ($\mathrm{Sr/Ca} \times 10^3 = 10.5 - 0.0604 \times \mathrm{SST}$; Alibert and McCulloch, 1997; Gagan et al., 1998; Marshall and McCulloch, 2002), giving the same average temperature of 25.4 °C for the last 280 yr. The higher sensitivity of the Flinders calibration (0.0451 versus 0.064 mmol/mol/°C), however, results in slightly greater SST variability. For comparison, we also correlated our coral Sr/Ca record to the IGOSS dataset (Reynolds and Smith, 1994) for the same time period and obtained a very similar equation ($\mathrm{Sr/Ca} \times 10^3 = 10.05 - 0.0431 \times \mathrm{SST}$; $r = 0.96$).

In order to test the robustness of the monthly-derived Sr/Ca calibration to infer past SST changes, we compared the 5-year Sr/Ca-SSTs estimates with 5-year average SSTs from the HadlSST1.1 data set for a location centered at 17.5° S, 148.5° E (Rayner et al., 2003). With the exception of the youngest three 5-year intervals, the Sr/Ca-SSTs are consistently lower (~0.7 °C) than the instrumental data. Despite differences in the absolute SST values, there is a general agreement in the long-term variations recorded by the instrumental and coral records. In fact, regression of Sr/Ca ratios and HadlSST1.1 temperatures at the lower frequencies used in this study (5 years) produced a calibration equation of $\mathrm{Sr/Ca} \times 10^3 = 10.306 - 0.0517 \times \mathrm{SST}$, $r = 0.73$, which compares very well with previous published calibrations in this area. Although the correlation coefficient is lower than that obtained with the monthly calibration, the use of this calibration instead of the monthly-derived equation is probably more meaningful for the study of long-term SST changes. It has to be stressed, however, that the use of one calibration or another will only affect the absolute SST, shifting the record only by a few tenths of a degree. For the present study, this is not a critical issue since we focus on relative temperature changes and long-term variability. In order to obtain the best possible SST estimate, however, we used an average of accepted SST calibrations for the GBR region (including this new

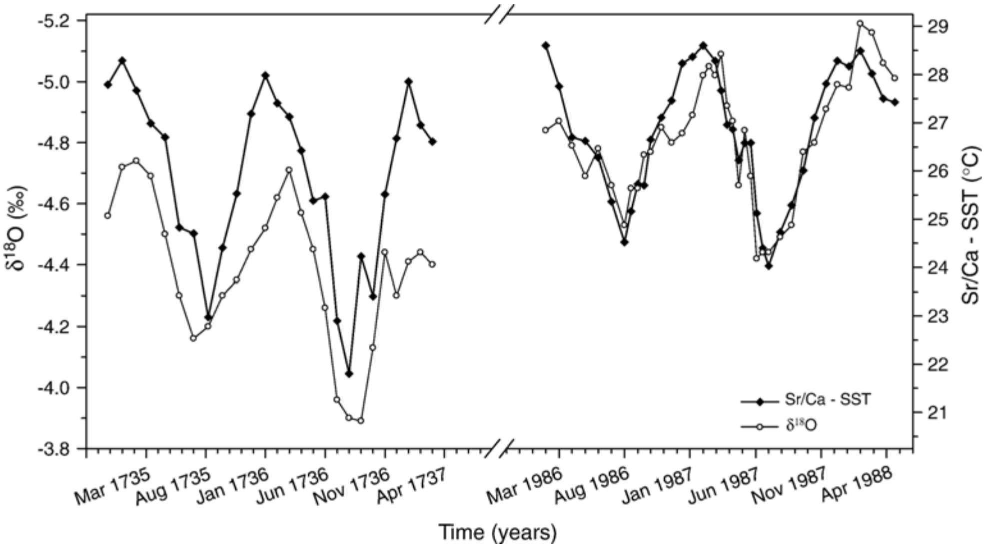

Fig. 4. Comparison of high-resolution Sr/Ca (thick line) and $\delta^{18}O$ (thin line) records for two periods of the Flinders record: 1735–37 A.D. (left) and 1986–88 (right). For the older period, Sr/Ca-SST estimates are about 1 °C colder than present estimates. The coral $\delta^{18}O$ records also reflects the decrease in temperature for 1735–37 but the observed $\delta^{18}O$ enrichment is mainly an indication of high salinity waters.

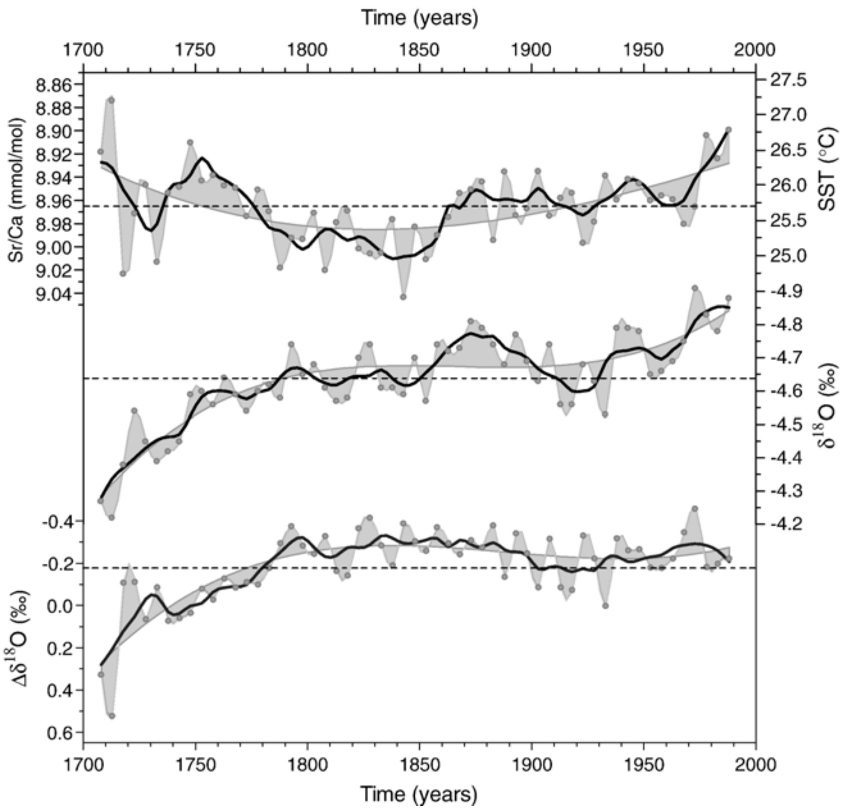

Fig. 5. Comparison of coral Sr/Ca-SST, δ^{18}O and δ^{18}O residuals ($\Delta\delta^{18}$O) from Flinders Reef. The long-term mean is represented by a third-polynomial fit with decadal/multidecadal variability superimposed on this trend. The 5-year record was also smoothed by a 9-point running mean (thick solid line). Positive $\Delta\delta^{18}$O values indicate more saline waters (see text for a more detailed description). Dashed lines show average values for each record.

calibration from Flinders Reef), instead of relying on a single coral and a relatively short 2-year high resolution Sr/Ca record. The calibration equations previously published from this area are from Davies Reef (Alibert and McCulloch, 1997), Orpheus Island (Gagan et al., 1998) and Myrmidon Reef (Marshall and McCulloch, 2002). The average of these calibrations and the new calibration from Flinders Reef provides the equation $Sr/Ca \times 10^3 = 10.43 - 0.057 \times SST$ which is used here to convert the Sr/Ca record to SST.

In addition to the recent period, 1986–1988, studied at high resolution, we also measured Sr/Ca and δ^{18}O every mm over the period 1735–1737 (Fig. 4). For this period, the Sr/Ca ratios show larger seasonal variability compared to 1986–88; this is mainly reflected in colder SSTs during the 1735–37 winters. The δ^{18}O record shows significant coral ^{18}O enrichment in the oldest part of the record for both winter and summer, with a mean δ^{18}O increase of 0.43‰ that exceeds the change expected solely from the Sr/Ca-derived SSTs. Thus, this δ^{18}O change can be attributed to a shift to more saline waters as a result of a change in the precipitation-evaporation regime. This increase in salinity may be due to either enhanced evaporation (although this explanation is unlikely, as average SSTs were lower than today) or reduced precipitation during the summer wet season. The period 1730–1740 was identified as especially dry in a record of Queensland summer rainfall obtained from luminescent bands in corals from the central GBR (Hendy et al., 2003). According to our reconstructed 5-year coral records, these conditions seem to have persisted for several years as confirmed by the reconstructed 5-year coral records (see further discussion below and Fig. 5).

3.2. 5-year intervals back to 1708 A.D.

3.2.1. Long-term trends

Low resolution Sr/Ca and δ^{18}O analyses were performed in 5-year bulk samples, extending back to 1708 A.D. (Fig. 5). Although the Sr/Ca and δ^{18}O records showed some similarities, in particular during

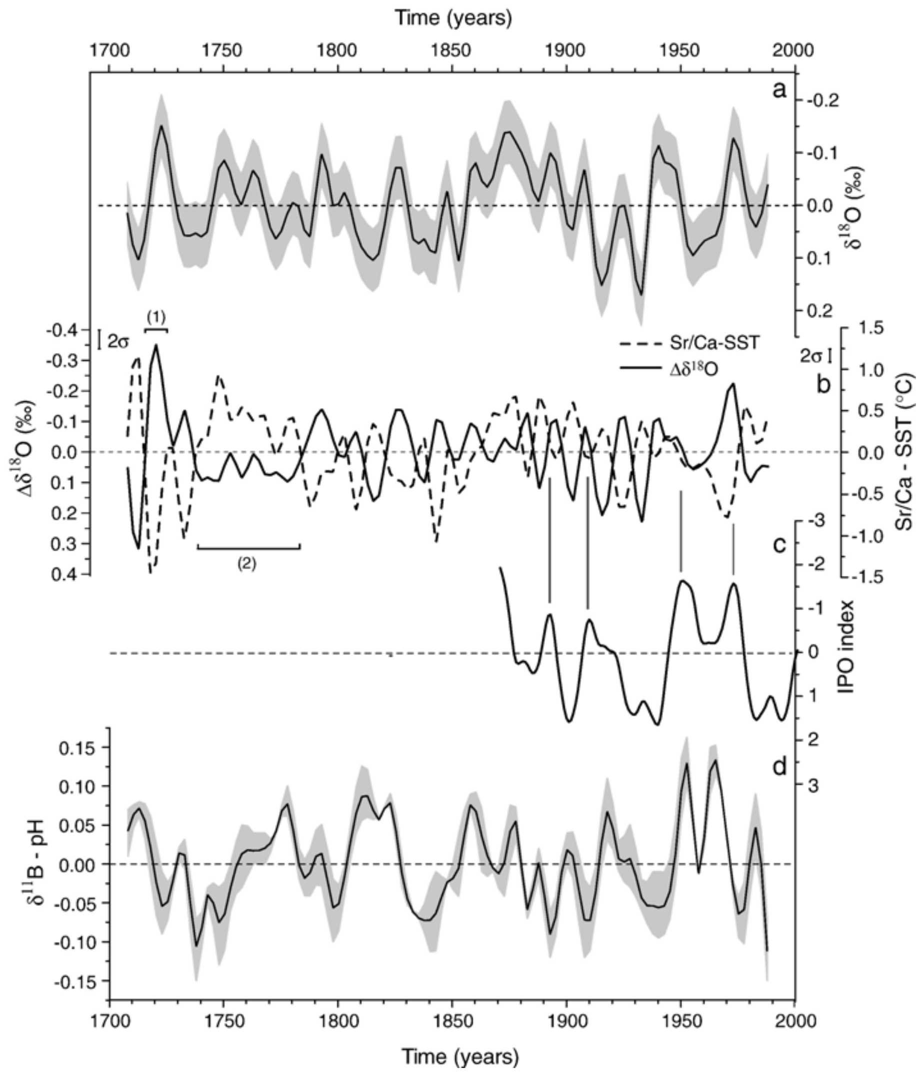

Fig. 6. Comparison of interdecadal variability in detrended Flinders Reef coral δ^{18}O (a), Sr/Ca and $\Delta\delta^{18}$O (b) records and the IPO index (c) from Power et al. (1999). Records were detrended by a third-degree polynomial fit (see also Fig. 5) and spline interpolated. The shaded area represents the 2σ analytical error envelope associated with each measurement. For the Sr/Ca and $\Delta\delta^{18}$O, the error is indicated with vertical bars for clarity ($2\sigma_{SST}$=0.14 °C and $2\sigma^{18}_{\Delta\delta O}$=0.064‰). At Flinders Reef, there is a significant correlation between SST and salinity (r=−0.74, n=57) with cool temperatures during wet periods (1) and warm temperatures during dry periods (2). d) Anomalies of surface-ocean pH derived from coral δ^{11}B (Pelejero et al., 2005). Vertical lines represent periods of negative IPO index, which correspond to fresher conditions (negative $\Delta\delta^{18}$O) at Flinders Reef.

the late-1800s and the 20th century, other parts of the record show little agreement, reflecting the effect of both temperature and seawater isotopic composition on the Flinders δ^{18}O record. Using our Sr/Ca-SST estimates, the temperature component of the δ^{18}O record can be subtracted and the residual δ^{18}O signal ($\Delta\delta^{18}$O) can be used to infer changes in salinity (a parameter mainly driven by changes in the evaporation–precipitation balance, but also by vertical/horizontal mixing of different water masses). We deconvolved a salinity record following examples from McCulloch et al. (1994) and Gagan et al. (1998) (Fig. 5). The residual δ^{18}O was calculated using the equation $\Delta\delta^{18}O=\partial\delta^{18}O/\partial SST*(SST_{\delta^{18}O}-SST_{Sr/Ca})$, and the Sr/Ca-SST calibration described in the previous section and the δ^{18}O-SST slope of −0.18‰ per °C derived for *Porites* sp. (Gagan et al., 1998). In Fig. 5, positive $\Delta\delta^{18}$O values indicate the presence of more saline waters, whereas more negative values are interpreted as a freshening of the coral reef waters. For the whole

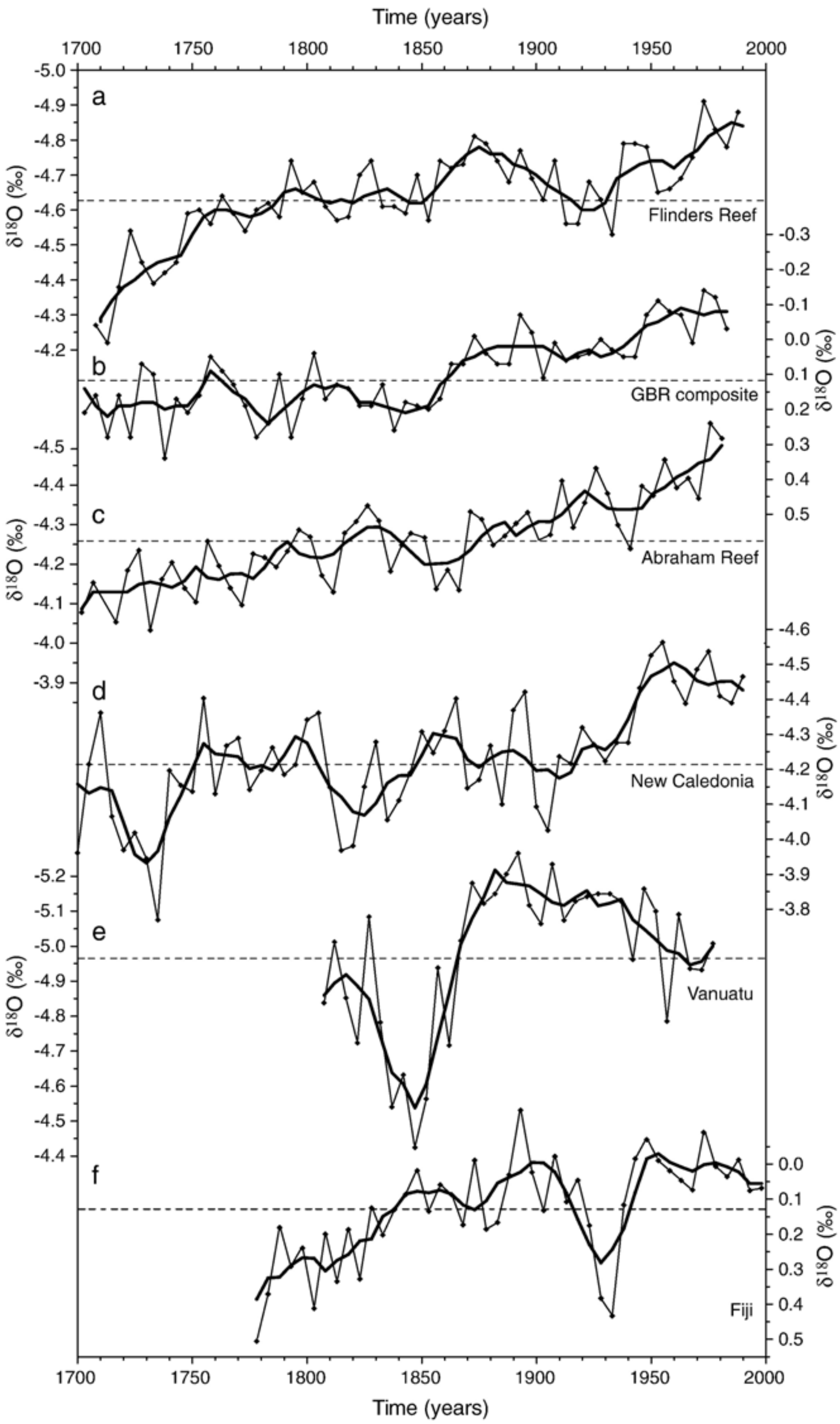

Fig. 7. Synthesis of multi-century trends in SST and SSS for the tropical SW Pacific region; a) Flinders Reef, this study (17° S, 148° E), b) Great Barrier Reef composite (Hendy et al., 2002) (18° S, 147° E), c) Abraham Reef (Druffel and Griffin, 1999) (22° S, 153° E), d) New Caledonia (Quinn et al., 1998) (22° S, 166° E), e) Vanuatu (Quinn et al., 1993, 1996) (15° S, 167° E), f) Fiji (Bagnato et al., 2005) (17° S, 179° E). All records were recalculated to obtain 5-year periods (thin solid lines). The 5-year records were also smoothed by a 9-point running mean (thick solid line).

record, the $\Delta\delta^{18}O$ explains 65% of the variance displayed by the $\delta^{18}O$ signature.

Estimates of Sr/Ca-SST appear to show a long-term trend towards warmer temperatures of the 20th century (~1 °C in 150 yr, taking into account the third-degree polynomial fit shown in Fig. 5 that was used to detrend our coral records). A trend towards more negative $\delta^{18}O$ values (warmer and/or less saline conditions) is also observed in the isotopic record over the same time period. If interpreted only in terms of temperature, the $\delta^{18}O$ decreasing trend of ~0.15‰ would translate into a ~1 °C increase in temperature (0.17–0.18‰ per °C; Gagan et al., 1998; Quinn et al., 1998), which compares well with the temperature change predicted by the Sr/Ca record and thus, suggests no significant long-term change in salinity for at least the last 150 years (Fig. 5; bottom panel). Superimposed on this trend are significant decadal and multidecadal changes that we discuss in the next section. The coldest conditions of the past 280 yr are recorded during the late 1700 s and the first half of the 19th century.

For the oldest section of the record, between 1700 and 1850, the effect of both temperature and salinity in the coral $\delta^{18}O$ signal becomes apparent, with a particularly marked disagreement between the Sr/Ca and the $\delta^{18}O$ records during the 18th century. At this time, the Sr/Ca-SST record exhibits temperatures warmer than average, while the oxygen isotopic record presents the highest values of the entire record with a secular depletion of about 0.35‰ from 1700 to 1800 (Fig. 5). In this case, the enriched $\delta^{18}O$ values are better explained by the presence of more saline waters during most of the 18th century (positive $\Delta\delta^{18}O$ values, Fig. 5). This is also confirmed by the monthly resolution data for that period (Fig. 4), as shown in the previous section. Once the effect of temperature has been removed from the $\delta^{18}O$ record, and due to the counteracting effect of temperature and salinity in the coral isotopic composition at this time, the residual $\delta^{18}O$ change between 1700 and 1800 would be of 0.5‰ (Fig. 5). After 1800, salinity remains, on average, more or less constant until today (Fig. 5). Although the secular $\delta^{18}O$ trend is consistent, caution is required when interpreting the large $\delta^{18}O$ change at the bottom of the record in terms of absolute values. In particular, the high $\delta^{18}O$ values of the two oldest samples might be partly influenced by a slower skeletal extension rate between 1708 and 1718 (9 mm yr^{-1}) compared with the rest of the record (12 mm yr^{-1} on average). We do not expect, however, kinetic effects to be very important since the $\delta^{13}C$ record (not shown) present fairly constant values at the bottom of the record despite the change in extension rates (corals displaying slower extension rates also present higher mean $\delta^{13}C$ values). On the other hand, anomalously high $\delta^{18}O$ values are frequently associated with the presence of secondary aragonite as consequence of marine diagenesis. If that was the case, Sr/Ca ratios would be greatly affected as well and deviated towards high Sr/Ca values. The Sr/Ca record, however, present the lowest values at the bottom of the record, ruling out any influence of diagenesis (Fig. 5).

Recently, Sr/Ca and $\delta^{18}O$ coral records from the GBR also identified higher salinities during the late 18th century followed by a rapid freshening ($\delta^{18}O$ depletion) of surface waters after 1850–70 A.D. that has persisted to the present day (Hendy et al., 2002; see further discussion below and Fig. 7). The authors interpreted this as a decrease in evaporation rates through a weakening in trade winds and ocean circulation at the end of the Little Ice Age. In the Flinders coral, however, the $\delta^{18}O$ shift also observed at 1850 A.D. does not seem to be due to a salinity change (there is no change in the $\Delta\delta^{18}O$ record) but to a temperature increase as shown by parallel changes in both $\delta^{18}O$ and Sr/Ca records at that time (Fig. 5). The subsequent 20th century warming recorded at Flinders Reef in the Sr/Ca and $\delta^{18}O$ records occurs in two steps: an initial warming that commences between 1920 and 1925 and a final warming from about 1965–1975 to the present. This feature has also been recorded in a Sr/Ca record (Hendy et al., 2002) and a $\delta^{18}O$ record (Druffel and Griffin, 1999) from the GBR and in $\delta^{18}O$ records from tropical sites in the Indian Ocean (Charles et al., 1997) and the eastern Pacific (Linsley et al., 2000). Notwithstanding the low resolution of our records, the shift observed from 1965–1975 towards warmer and wetter conditions could be related to the 1976 shift widely reported in the tropical region and related to ENSO-decadal variability (Cole et al., 1993; Cole et al., 2000; Urban et al., 2000).

3.3. Interdecadal variability

The IPO represents a pattern of SST variation over the Pacific Ocean, so that when the equatorial Pacific is warm and the southwest and central North Pacific are cold, the index is positive, while opposite sign tropical SST anomalies are represented by a negative IPO index (Folland et al., 1999; Power et al., 1999). The most recent and best-documented change in the IPO index occurred in 1976. This regime shift was characterized by an increase in tropical SSTs and the development of more frequent and stronger El Niño versus La Niña events (Trenberth and Shea, 1994; Guilderson and Schrag, 1998). In the North Pacific, warmer than average SSTs along the west coast of North America also caused dramatic changes in marine biological populations (Mantua et al., 1997). This regime shift was due to a major oceanic and atmospheric reorganization that induced climatic and biological changes over the Pacific region (see Miller and Schneider (2000) for a review). Such changes are now recognised to have occurred several times during the last century as shown by the instrumentally-derived IPO index, that extends back to 1871 (Folland et al., 1999; Power et al., 1999; Fig. 6c) and suggested to have occurred over past few centuries (Biondi et al., 2001; D'Arrigo et al., 2001; MacDonald and Case, 2005).

In Fig. 6, the long-term trend of the Flinders coral records has been removed using a polynomial fit (see also Fig. 5) and the detrended records are compared with the evolution of the IPO index as defined by Power et al. (1999). At these multidecadal timescales, discrepancies between the Sr/Ca and δ^{18}O records indicate that the δ^{18}O of seawater, and not temperature, is the most likely source of coral δ^{18}O variability. For a better comparison of SST and salinity anomalies, the Sr/Ca and the residual δ^{18}O records have been plotted together in Fig. 6b. The coral records display interdecadal variability with typical temperature and salinity changes of around 0.7 °C and 0.15‰, respectively. The interdecadal variability observed in the salinity record ($\Delta\delta^{18}$O) is significant, nearly always inversely correlated with changes in SST ($r=-0.74$, $n=57$), with colder SSTs recorded during low salinity periods (depleted $\Delta\delta^{18}$O values) and warmer SSTs when waters were saltier (enriched $\Delta\delta^{18}$O values). In this oceanographic setting, salinity fluctuations are mainly controlled by the strength of the Australian summer monsoon (Wolanski, 1994) and thus, the $\Delta\delta^{18}$O record can be mainly interpreted in terms of changes in precipitation (other effects like evaporation and water advection are also discussed below).

Comparison of the detrended Sr/Ca and $\Delta\delta^{18}$O records with the IPO index reveals some similarities between the records although the IPO does not show the same variability, with coral proxies showing slightly higher-frequency variability than the IPO (Fig. 6c). In general, periods of negative IPO are associated with more depleted values of $\Delta\delta^{18}$O (lower salinity) and cooler SSTs, with the exception of an "anomalous" warm interval recorded during 1935–1950 (Fig. 6b and c). It has to be noted here that, *a priori*, Flinders Reef was not expected to be a very sensitive area to record changes in interdecadal SSTs, since it is an area with a small gradient of SST anomalies (see Fig. 1 from Folland et al. (2002) and Fig. 2 from Power et al. (1999) and may be more sensitive to changes in salinity, see below).

The observed freshening during the cold phases of the IPO (i.e. 1946–1976) is consistent with an observed increase in precipitation over northeast Australia at these times (Latif et al., 1997; Power et al., 1999; Arblaster et al., 2002), when ENSO teleconnections are strong and the frequency and strength of individual La Niña events are greater than during positive IPO phases. Such interdecadal modulation of ENSO and its impact on Australia's climate also increases the flood risk in New South Wales (eastern Australia) during the negative IPO phases (Kiem et al., 2003). In addition, Folland et al. (2002) also found that the location of the South Pacific Convergence Zone (SPCZ) varies in parallel with changes in the IPO, moving southwest of its mean position during the negative phase (as it does during La Niña on an interannual timescale). In contrast, a shift to positive IPO values (i.e. 1976) brings lower rainfall to the region southwest of the SPCZ due to a northeast displacement of the SPCZ (Salinger et al., 2001; Folland et al., 2002). The resulting decrease in precipitation during a warm IPO phase is translated into higher salinities in the Flinders Reef region and recorded by the coral proxies as δ^{18}O and $\Delta\delta^{18}$O enrichments (Fig. 6).

High interdecadal variability has also been found in a seawater pH reconstruction based on boron isotopes from the same Flinders Reef coral (Pelejero et al., 2005; Fig. 6d). This record shows a strong 50 yr cycle very likely related to changes in the flushing rate of reef waters associated with the distinctive oceanic conditions that developed during each IPO phase. Changes in pH appear to have varied at a lower-frequency than changes in SST and salinity and are more similar to changes in the IPO phase. Despite this, the changes in the ventilation of the reef waters may have also left an imprint on the Sr/Ca and δ^{18}O records, amplifying the original signal. Low seawater pH levels, that were ascribed to periods of low flushing rates (longer residence time of waters in the reef) (Pelejero et al., 2005), would also increase the temperature and salinity in the reef due to excess heating and evaporation (i.e. ~1980, 1930, 1905, 1890). On the contrary, a better ventilation of the reef with waters advected from the east would change temperature and salinity in the opposite direction.

Decadal-scale fluctuations have also been documented in several coral proxy records from New Caledonia (Quinn et al., 1998), the central GBR (Hendy et al., 2002) and Rarotonga and Fiji (Linsley et al., 2004; Bagnato et al., 2005), although these changes do not always occur at the same time in all records. The new data from Flinders Reef exhibit significant variability during the 20th century but also present periods of lower interdecadal variability, for example, during 1735–1780 and 1850–1880 (Fig. 6b). In this sense, Linsley et al. (2004) concluded that the spatial pattern of the IPO has probably varied over time, identifying times of poor geographic expansion and poor reproducibility between coral records, as appears to be the case prior to 1880.

3.4. Comparison with other coral records

Century-long coral-based reconstructions from the southwest Pacific (the GBR (Druffel and Griffin, 1999; Hendy et al., 2002), New Caledonia (Quinn et al., 1998), Vanuatu (Quinn et al., 1993, 1996) and Fiji (Bagnato et al., 2005)) are plotted in Fig. 7 and compared with the Flinders Reef record. For clarity, we have only plotted $\delta^{18}O$ records, since most of the coral records available in the literature are based on this proxy and only a few combine the isotopic analyses with Sr/Ca ratios. The interpretation of $\delta^{18}O$ records as either temperature or salinity, however, may be valid only for some sites and timescales but, in general, the skeletal $\delta^{18}O$ signal will be a combination of both effects. Crowley et al. (1999) found that, despite the strong correlations observed between coral $\delta^{18}O$ and SST on a seasonal cycle, on interannual and decadal timescales salinity changes became more important and often override the effect of any change in SST.

In the GBR, a composite of eight Sr/Ca and $\delta^{18}O$ records (Hendy et al., 2002) provided a salinity record that shares 80% of its variance with the original coral $\delta^{18}O$ record (Fig. 7b). At Flinders Reef, however, temperature is also an important source of coral $\delta^{18}O$ variability, at least in the most recent part of the record (Figs. 5 and 7a). Large decadal $\delta^{18}O$ fluctuations in the coral from New Caledonia were mainly interpreted in terms of temperature variability and correlated to changes in the PDO/IPO index (Quinn et al., 1998; Linsley et al., 2004). At this location, IPO-related changes in SST will be of opposite sign to those occurring at Flinders Reef (New Caledonia warms during a negative IPO phase while Flinders cools, and vice versa). Moreover, the magnitude of the changes is also expected to be greater in New Caledonia than in Flinders, as can be seen in Fig. 7. This is because first, New Caledonia is located within the area of larger SST anomalies, where IPO variability is greater (see Fig. 1 from Folland et al. (2002) and Fig. 2 from Power et al. (1999)) and second, salinity changes due to precipitation anomalies associated with the interdecadal displacement of the SPCZ (Folland et al., 2002) will also shift the coral $\delta^{18}O$ signature in the same direction as temperature. In this location, warmer (cooler) periods are also wetter (drier) than normal, causing coral $\delta^{18}O$ changes of the same sign. In the Flinders Reef coral, however, multidecadal warm and dry anomalies affect the coral $\delta^{18}O$ in opposite directions (Fig. 6).

Changes in the amplitude of these decadal variations also seem to have varied with time in some of the records. Larger decadal variability is observed after 1870 in a coral from Abraham Reef in the Great Barrier Reef (Druffel and Griffin, 1999) and also in $\delta^{18}O$ records from Fiji and Rarotonga (Linsley et al., 2004; Bagnato et al., 2005) (Fig. 7). This change also corresponds to a $\delta^{18}O$ shift recorded in several coral records towards the warmer/wetter conditions of present times (Fig. 7) and may be indicative of a major reorganization of the decadal mode of the Pacific climate system after 1870 (Linsley et al., 2004).

4. Conclusions

We reconstructed a 280-year proxy record of SST and seawater salinity from Sr/Ca and $\delta^{18}O$ measurements on a coral core from Flinders Reef in the western Coral Sea. The pent-annual sampling resolution allows the study of long-term changes and multidecadal variability in this region of the South Pacific. Together with the 20th century warming, the most prominent feature registered at Flinders Reef is a prolonged period of temperatures and salinities higher than average recorded during most of the 18th century. This is likely caused by a decrease in precipitation during the wet season in Australia, as suggested by the monthly Sr/Ca and $\delta^{18}O$ measurements.

On interdecadal timescales, northeast Australia has experienced alternate periods of warm/dry versus cool/wet conditions in phase with changes in the IPO (Power et al., 1999). During negative (positive) IPO phases, northeast Australia receives more (less) rainfall and experiences cooler (warmer) conditions. Although not all these changes are synchronously recorded at Flinders Reef, the Sr/Ca and $\delta^{18}O$ records show a strong relationship on these timescales with light isotopic values (less saline) occurring at times of high Sr/Ca ratios (lower SST). This alternation between warm/dry and cool/wet periods has operated, at least, for the last 280 yr although the amplitude of the SST and salinity changes has varied over time; for instance, during the second half of the 18th century when the amplitude was lower. These results diverge from the general view of warm/wet and cool/dry conditions often described for low latitude areas.

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