

Variations in massive *Porites* growth rates at Hainan Island, northern South China Sea

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ABSTRACT: Annual density banding in massive coral skeletons provides a means to retrospectively monitor coral growth rates. In this study, we present new records of annual skeletal density, linear extension and calcification rates for 16 *Porites* spp. coral cores from northeastern Hainan Island, northern South China Sea. Based on average growth characteristics from 1948 to 2001, *P. lobata* had significantly higher linear extension and calcification rates and lower density than *P. lutea*. We also found evidence of an age-related effect on growth, whereby skeletal density decreased and linear extension rate increased through time. This did not affect calcification rates. The average calcification rate for northeastern Hainan Island *Porites* matches that expected for Indo-Pacific *Porites* based on average sea surface temperatures (SST) from 1961 to 1990. After removal of the ontogenetic trends, average 16-core calcification rates from 1923 to 2002 showed an initial increase, matching observed SST warming. After 1982, however, calcification significantly decreased, although SST did not continue to warm. We suggest that the lower calcification rates from 1983 to 2002 may be a response to eutrophication of coastal waters as a result of extensive coastal aquaculture development. In summary, our new growth records from Hainan Island show that, despite species differences, calcification rates were typical of Indo-Pacific *Porites* but that in the latter half of the 20th Century, calcification rates have likely responded to both globally and locally induced changes in the marine climate experienced by the corals.

KEY WORDS: *Porites* spp. · Calcification · Growth rates · South China Sea · Temperature · Aquaculture

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INTRODUCTION

The surface ocean is changing for tropical coral reef ecosystems as the global climate system responds to increasing levels of atmospheric greenhouse gases due to human activities (Stocker et al. 2013). These changes, primarily warming sea surface temperatures (SST) and progressive ocean acidification, are expected to have major consequences for the maintenance of healthy tropical coral reef communities and ecosystems into the future (Hughes et al. 2003, Hoegh-Guldberg et al. 2007, Fabricius et al. 2011). In addition to global-scale changes, many

tropical coral reefs, especially those of East Asia, are under increasing pressures from local activities such as coastal development, land- and marine-based pollution, overfishing and destructive fishing practices (Wilkinson 2008, Chou 2010, Burke et al. 2011, Hughes et al. 2013).

At the heart of tropical coral reefs is sustained calcification (production of calcium carbonate skeleton) that occurs fast enough to withstand the natural forces of biological and physical erosion (Pratchett et al. 2015). However, this fundamental physiological process is likely to be increasingly compromised by ongoing local and global changes to the marine envi-

ronment. Certain long-lived, massive corals contain annual density bands which can provide historical perspectives (retrospective monitoring) of coral growth rates in space and time (Knutson et al. 1972, Budde-meier & Kinzie 1976). For example, average SST has been identified as a primary driver of spatial variations in massive coral growth rates (e.g. Carricart-Ganivet 2004, Lough 2008). Average growth rates can also vary in relation to other environmental gradients such as proximity to land (Lough & Cooper 2011, Lough & Cantin 2014).

Using annual density bands, several studies have documented recent declines in growth rates at various coral reef sites around the world (e.g. Cooper et al. 2008, De'ath et al. 2009, 2013, Cantin et al. 2010, Castillo et al. 2011, 2012, Carricart-Ganivet et al. 2012, Shi et al. 2012, Tanzil et al. 2013). SST at these sites have already significantly warmed. Other studies have found no changes in growth rates where SST have not significantly warmed (e.g. Helmlé et al. 2011) or even initial increases in growth rates associated with warming SST (e.g. Lough & Barnes 2000, Cooper et al. 2012). Declines in growth rates with warming SST can arise from setbacks in growth due to thermal stress causing coral bleaching (Carilli et al. 2009, 2012, Castillo et al. 2011, 2012, D'Olivo et al. 2013, Cantin & Lough 2014) and corals exceeding their thermal optimum (Jokiel & Coles 1977, Cooper et al. 2008, Lough & Cantin 2014).

In this study, we focussed on growth rates of massive *Porites* spp. from northeastern Hainan Island, China. Annually-banded massive corals can provide records of coral growth rates and a range of environmental and climatic proxies from various isotopic and geochemical tracers included in the coral skeleton (Lough 2010). Previous studies of modern massive *Porites* records from Hainan Island have primarily focussed on the latter application (Wei et al. 2000, Peng et al. 2001, Shimamura et al. 2005, 2008, Su et al. 2006, Liu et al. 2008, 2011, Sun et al. 2008, Deng et al. 2013, Song et al. 2014, Chen et al. 2015). The only study specifically investigating growth rates (Nie et al. 1997) measured linear extension rates in 3 *P. lutea* cores from Yulin Harbour (southern Hainan Island) back to the 19th century and reported a significant correlation with temperature. Here we present growth characteristics for 16 massive *Porites* coral cores collected from the northeastern coast of Hainan Island in the northern South China Sea. This is the first such well-replicated growth rate study for this region. We examined average growth characteristics (linear extension, skeletal density and calcification), possible age-related effects, variations with species (*P.*

lobata and *P. lutea*), relationships between growth variables, conformity with the general Indo-Pacific relationship between average calcification and average SST, growth variation through time and possible drivers of observed changes.

MATERIALS AND METHODS

Regional setting

The South China Sea (SCS) is influenced by the Asian monsoon and the oceanographic circulation of the northwestern Pacific. The winter monsoon (November to April) is associated with cold, dry northeast winds from the Siberian and Mongolian Plateaus, while the summer monsoon (May to October) is associated with warm, moist southwesterly winds from the tropical oceans. Our sampling sites were located on the eastern side of Hainan Island in the northern SCS (Fig. 1), where the main surface ocean currents are driven by these monsoon winds. These currents are from the southwest in summer and from the northeast in winter (Hu et al. 2000). SST and sea surface salinity (SSS) are thus strongly influenced by the prevailing currents, with highest SST and lowest SSS in summer and cooler SST and higher SSS in winter. Annual rainfall averages ~1800 mm, with a seasonal maximum during the summer southwesterly monsoon. In addition, the island is affected by tropical cyclones between June and November which can contribute approximately a third of the annual total rainfall (Wu et al. 2007).

Coral cores

Coral cores were collected from the fringing reef offshore of Qingge-Oucun, eastern Hainan Island, between 2002 and 2004. The reef is ~6 km long and varies between 0.03 and 0.2 km in width, with water depth above the reef ranging from 2 to 15 m. The reef system supports 45 genera and 128 species of coral. Cores were collected from 16 living massive *Porites* colonies using a petrol motor-powered hydraulic pump driving a hydraulic drill rig. Cores were ~5.5 cm in diameter and averaged 1.3 m in length (range 0.4–1.9 m; Table 1). The average height of the colonies from which the cores were taken was 1.5 m (range 0.6–2.1 m), so the cores averaged 90% (range 77–93%) of the sampled colony height. Five cores were collected from Oucun (OC) and 11 cores from Qingge (QG), ~4 km to the south. Cores were mounted, and

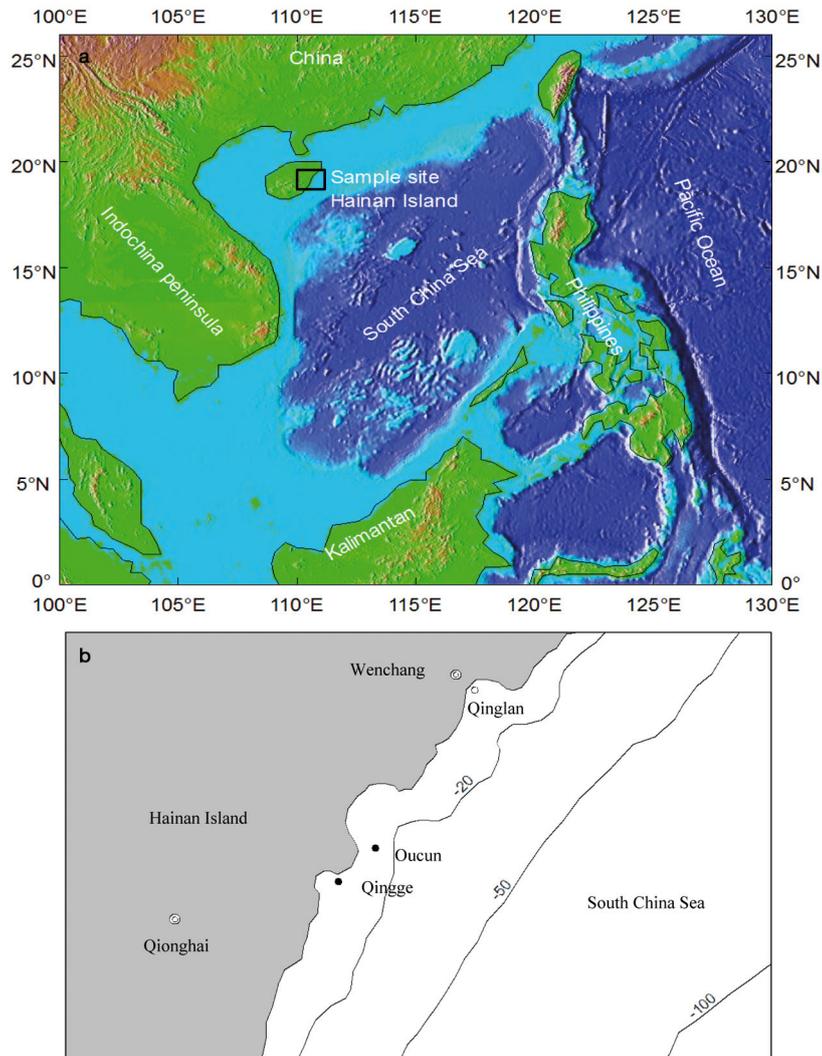


Fig. 1. (a) Hainan Island and the northern South China Sea showing sampling area (box), and (b) location of coral sampling sites (Oucun and Qingge) off eastern Hainan Island

slices 0.5 cm thick were removed and cleaned with several rinses of fresh water and then distilled water to remove any remaining residue from sawing and other possible contaminants. Each core was identified to species level from observation of the colonies *in situ* and subsequent microscopic examination of the cores. Seven cores were identified as *P. lobata* and 9 cores as *P. lutea* (Table 1).

Measurement of coral growth parameters

After drying, coral core slices were X-rayed using a medical HITACHI X-radiography machine at 50 kV voltage, 50 mA current for 0.04 s. The X-radiographic

images were scanned using a UMAX Astra 4000U scanner to produce positive digital density images. We then selected optimum tracks along major growth axes for measuring grey-scale values on the digital images following the approach of Sun et al. (2002) (Fig. 2).

We corrected for non-uniform irradiation of the X-ray film (the heel effect; Chalker et al. 1985, Carricart-Ganivet & Barnes 2007) by subtracting the background grey-scale values across the X-ray film from the measurements along the selected track. To convert the grey-scale values from the digital X-ray to absolute skeletal density, we followed the procedure of Sun et al. (2002): 0.5 cm cubes were cut from a previously measured growth axis of each coral slab. The dimensions of the cleaned and dried cubes were measured using high-resolution Vernier callipers, and the mass of each cube was measured with a digital electronic scale. The density of each cube was then calculated from the measured mass and volume. Using this standard, the grey scale values for each coral slice were converted to absolute skeletal density. Based on the date of sample collection and the distance vs. density time series, successive density bands were dated backwards in time.

From the density series, we calculated annual linear extension rate as the linear distance (cm yr^{-1}) between adjacent annual density maxima, and annual skeletal density (g cm^{-3}) as the average density between these maxima, and then derived the annual calcification rate ($\text{g cm}^{-2} \text{yr}^{-1}$) as the product of these 2 values (see Fig. S1 in the Supplement at www.int-res.com/articles/suppl/m546p047_supp.pdf). The depth of the living tissue layer (cm) was also measured at the outer surface of each core, using Vernier callipers, as the average of 3 measurements (Barnes & Lough 1992).

Environmental data

Monthly SST data were obtained from the HadISST data set (Rayner et al. 2003) for the 1° latitude by longitude box closest to the sampling site (centred on 19.5°N , 110.5°E). This data set, available from 1871,

Table 1. Coral core details and average (\pm SD) growth characteristics for the period 1948 to 2001. Core IDs indicate collection sites of Oucun (OC) and Qingge (QG), respectively

Core ID	Species	Collection date	Water depth (m)	Record period	Core length (cm)	Colony height (cm)	Tissue layer thickness (cm)	Extension (cm yr ⁻¹)	Density (g cm ⁻³)	Calcification (g cm ⁻² yr ⁻¹)
Oucun										
OC04A	<i>Porites lobata</i>	Jul 2004	10	1901 – 2003	186	205	0.80	1.81 \pm 0.12	0.98 \pm 0.06	1.77 \pm 0.17
OC031	<i>P. lutea</i>	Sep 2003	9	1887 – 2002	169	192	0.80	1.46 \pm 0.19	1.20 \pm 0.17	1.73 \pm 0.19
OC032	<i>P. lobata</i>	Sep 2003	5	1922 – 2002	143	160	0.60	1.79 \pm 0.23	1.13 \pm 0.08	2.01 \pm 0.21
OC033	<i>P. lutea</i>	Sep 2003	5	1944 – 2002	84	96	1.60	1.43 \pm 0.14	1.10 \pm 0.06	1.58 \pm 0.19
OC034	<i>P. lutea</i>	Sep 2003	5	1891 – 2002	131	151	1.05	1.18 \pm 0.17	1.32 \pm 0.09	1.56 \pm 0.20
Qingge										
QG5	<i>P. lutea</i>	May 2002	2	1948 – 2001	43	55	0.60	0.80 \pm 0.07	1.32 \pm 0.08	1.04 \pm 0.14
QG041	<i>P. lutea</i>	Jun 2004	7	1921 – 2003	95	112	0.70	1.16 \pm 0.11	1.07 \pm 0.04	1.24 \pm 0.12
QG042	<i>P. lutea</i>	Jun 2004	7	1899 – 2003	129	140	1.15	1.24 \pm 0.12	1.27 \pm 0.08	1.57 \pm 0.19
QG043	<i>P. lobata</i>	Jun 2004	10	1928 – 2003	128	138	1.00	1.70 \pm 0.13	0.91 \pm 0.04	1.55 \pm 0.12
QG044	<i>P. lutea</i>	Jul 2004	9	1860 – 2003	151	168	0.75	1.02 \pm 0.23	1.26 \pm 0.09	1.27 \pm 0.24
QG045	<i>P. lobata</i>	Jul 2004	10	1898 – 2003	118	126	0.60	1.11 \pm 0.09	1.29 \pm 0.10	1.42 \pm 0.14
QG046	<i>P. lobata</i>	Jul 2004	12	1934 – 2003	128	144	0.75	1.80 \pm 0.19	0.97 \pm 0.05	1.74 \pm 0.18
QG047	<i>P. lobata</i>	Jul 2004	10	1889 – 2003	159	187	0.95	1.37 \pm 0.15	1.10 \pm 0.03	1.50 \pm 0.18
QG048	<i>P. lutea</i>	Aug 2004	11	1860 – 2003	140	151	0.80	1.02 \pm 0.26	1.19 \pm 0.09	1.21 \pm 0.28
QG049	<i>P. lutea</i>	Aug 2004	11	1876 – 2003	123	136	0.45	0.98 \pm 0.13	1.19 \pm 0.10	1.16 \pm 0.14
QG0410	<i>P. lobata</i>	Jul 2004	12	1923 – 2003	145	160	0.70	1.79 \pm 0.18	1.00 \pm 0.10	1.78 \pm 0.13

is based on *in situ* (e.g. ships of opportunity) and adjusted satellite SST observations, for more recent years, optimally interpolated to provide globally complete coverage.

As a measure of potential local changes in the marine environment, we considered the area used for aquaculture for the Qionghai city region from the 1950s (Statistical Bureau of Hainan Province, 2002, 2007). This encompasses our 2 study sites (Qingge and Oucun) and Baoao, and includes both freshwater and seawater aquaculture.

Analyses

To test for possible age effects in the growth records, we used the approach of Lough (2008). First, all time series for the 3 growth variables were standardised by the respective common period average (1948–2001). This allowed for differences in absolute growth values between individual coral cores. The series were then set to start in Year 1, regardless of actual start year, and averaged for 10 yr periods: Years 1–10, Years 11–20, through Years 91–100. The resulting time series were tested for significant linear trends. If there was no age effect, then this summation would be expected to produce a random time series with no significant trend.

Individually, all 16 annual density series showed a significant linear decreasing trend, and 12 of the 16

linear extension series showed a significant linear increasing trend (Fig. S2 in the Supplement). This was strongly suggestive of an age effect on skeletal density and linear extension rate. We therefore detrended each density and extension time series with a significant linear trend. The annual calcification time series were then recalculated from these detrended density and extension time series. All subsequent analyses were based on these detrended time series.

The length of dated coral growth variables varied amongst the 16 cores, with the longest record (QG044) starting in 1859 and the shortest (QG5) in 1948. We therefore used the period 1948 to 2001, common to all cores, for examining and comparing average growth characteristics amongst the 16 cores (Table 1). The 3 growth variables for each core were then converted to percentage growth anomalies from the base period average. This approach allowed for differences in average growth characteristics amongst the cores (e.g. Cooper et al. 2012). Average anomaly time series were calculated over the period 1923 to 2002, for which the majority of cores ($\geq 75\%$) provided continuous growth records.

Differences in average growth characteristics for *P. lobata* and *P. lutea* were tested for significance using the *t*-value for differences in means (Mitchell et al. 1966). The same test was used to determine the years of maximum significant change in successive 20 yr average series. Annual average time series were treated with a 10 yr Gaussian filter to emphasise

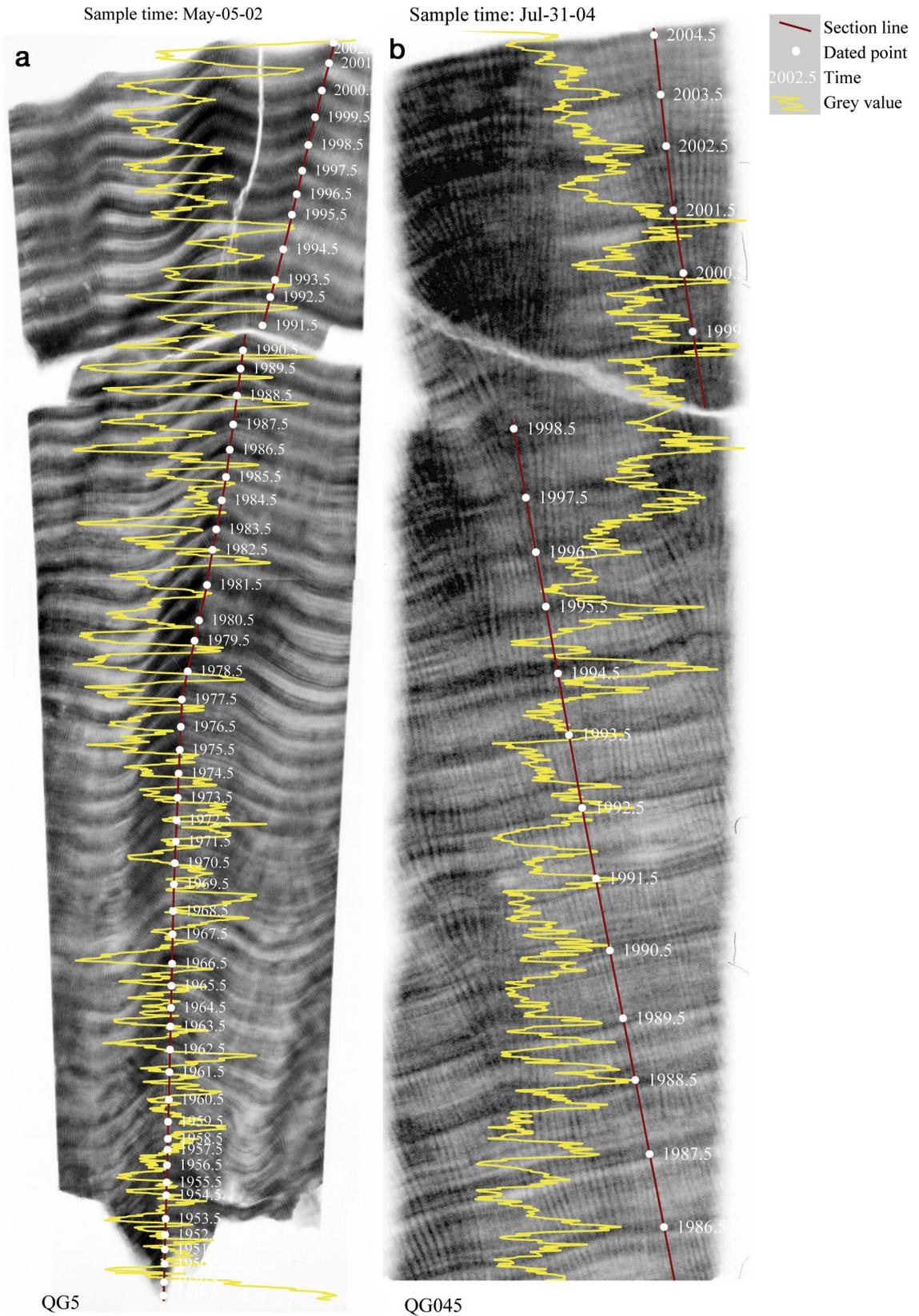


Fig. 2. X-ray positive print showing measurement transect (red line), grey-scale values (yellow line) and dated years (white) for the top sections of *Porites* cores (a) QG5 and (b) QG045

decadal variability. Linear correlation and regression analyses were used to determine relationships between growth variables and SST and to assess linear trends through time. When correlating time series, the effective degrees of freedom were adjusted for autocorrelation (Quenouille 1952), where present.

RESULTS

Evidence for age effects on growth characteristics

As one of the aims of this study was to examine temporal variations in growth records from the SCS coral cores, it was important to first identify whether any of the growth records was compromised by possible ontogenic (age-related) artefacts (see Lough 2008, Lough & Cooper 2011). Averaged across all cores, we found a significant ($p < 0.01$) increase in linear extension and significant decrease in skeletal density ($p < 0.01$) with increasing age (Fig. 3a,b). There was no significant linear trend in calcification with age (Fig. 3c). The decrease or increase tended to stabilise after ~40 to 50 yr. Thus, as found previously for massive *Porites* (Lough 2008), there does seem to be an age-related effect in these SCS cores, whereby extension tends to increase and density tends to decrease as the colony grows. This potential age-related artefact was also clearly evident in the individual annual density time series for all 16 cores and in annual linear extension for 12 of the 16 cores (Fig. S2 in the Supplement). We therefore removed the linear trend (where significant) from the density and linear extension time series and recalculated the annual calcification rates.

Average growth characteristics and species differences

Across all 16 cores, extension averaged (\pm SD) $1.36 \pm 0.37 \text{ cm yr}^{-1}$, density was $1.14 \pm 0.15 \text{ g cm}^{-3}$, calcification was $1.51 \pm 0.32 \text{ g cm}^{-2} \text{ yr}^{-1}$, and tissue layer thickness was $0.83 \pm 0.28 \text{ cm}$ (Table 2). Comparison of the growth characteristics for the 2 species showed that extension of *P. lobata* was significantly higher (at the 5% level) than that of *P. lutea* (difference = $+0.48 \text{ cm yr}^{-1}$, t -value = 3.16) as was calcification (difference = $+0.31 \text{ g cm}^{-2} \text{ yr}^{-1}$, $t = 2.09$). Density was significantly lower (difference = -0.16 g cm^{-3} , $t = 2.25$) but there was

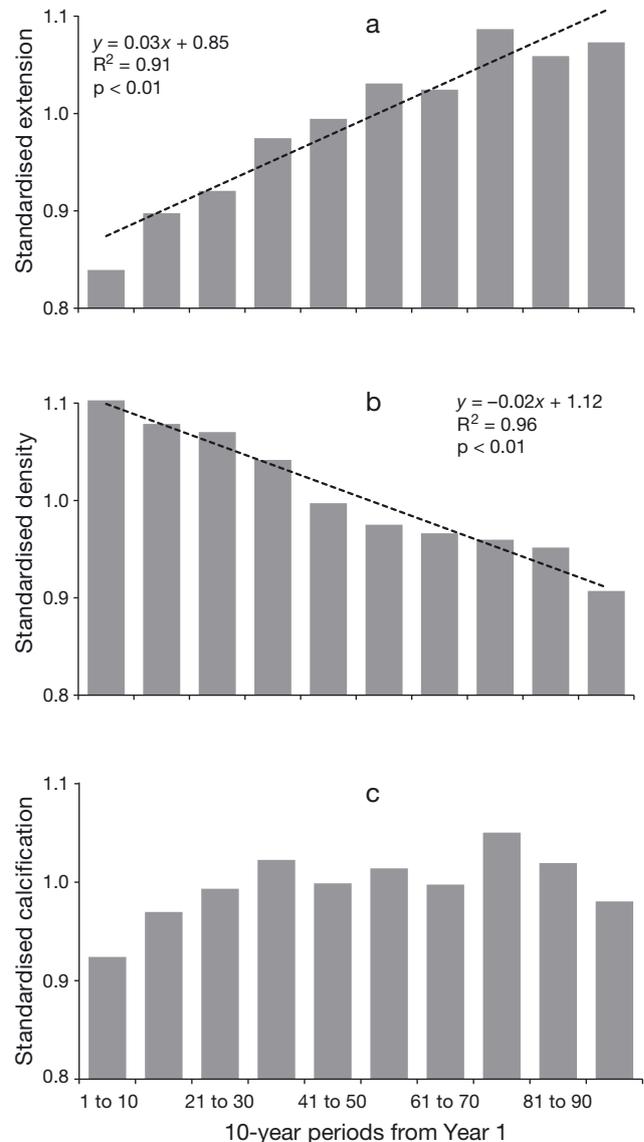


Fig. 3. Standardised (based on 1948 to 2001 average) 10 yr average growth values for 16 *Porites* cores with all time series set to start in Year 1 for (a) extension, (b) density and (c) calcification. Linear regressions are also shown where significant at the 5% level

Table 2. Average (\pm SD) growth characteristics for all 16 coral specimens (2 species from 2 sites) examined, for the period 1948 to 2001

	n	Extension (cm yr^{-1})	Density (g cm^{-3})	Calcification ($\text{g cm}^{-2} \text{ yr}^{-1}$)	Tissue thick- ness (cm)
All	16	1.36 ± 0.37	1.14 ± 0.15	1.51 ± 0.32	0.83 ± 0.28
<i>Porites lobata</i>	7	1.62 ± 0.30	1.06 ± 0.14	1.68 ± 0.25	0.77 ± 0.16
<i>P. lutea</i>	9	1.15 ± 0.26	1.21 ± 0.13	1.37 ± 0.30	0.88 ± 0.34
Oucun	5	1.53 ± 0.29	1.15 ± 0.15	1.73 ± 0.25	0.97 ± 0.39
Qingge	11	1.27 ± 0.37	1.14 ± 0.15	1.41 ± 0.29	0.77 ± 0.20

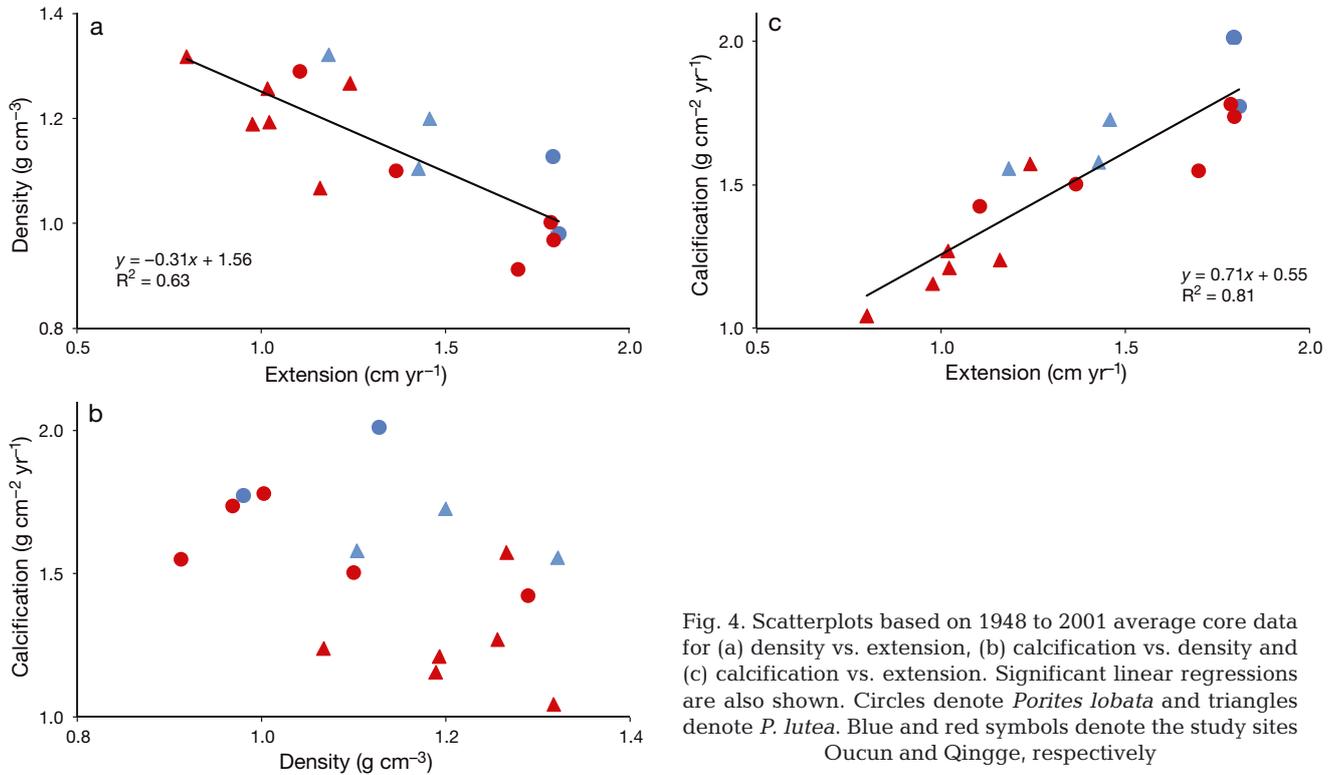


Fig. 4. Scatterplots based on 1948 to 2001 average core data for (a) density vs. extension, (b) calcification vs. density and (c) calcification vs. extension. Significant linear regressions are also shown. Circles denote *Porites lobata* and triangles denote *P. lutea*. Blue and red symbols denote the study sites Oucun and Qingge, respectively

no significant difference in tissue layer thickness (difference = -0.11 cm, $t = 0.740$). Comparison of the growth characteristics for the 2 sites showed that calcification at Oucun was significantly higher than at Qingge (difference = $+0.32$ g cm $^{-2}$ yr $^{-1}$, $t = 2.01$) but that there was no significant difference in linear extension (difference = $+0.26$ cm yr $^{-1}$, $t = 1.31$), density (difference = -0.01 g cm $^{-3}$, $t = 0.05$) or tissue layer thickness (difference = 0.20 cm, $t = 1.244$).

Relationships between growth characteristics

Linear extension and skeletal density were significantly inversely related (Fig. 4a, $p < 0.01$). There was no significant relationship between density and calcification (Fig. 4b, $p = 0.06$), and linear extension and calcification were significantly positively related (Fig. 4c, $p < 0.01$). There was no significant relationship between the 3 growth variables and the depth of the living tissue layer.

Comparison with Indo-Pacific *Porites* growth rates

Given average SST at the SCS site, average calcification rates for all 16 cores, and for *P. lobata* and *P. lutea* considered separately, fall close to the regres-

sion line (Fig. 5). Thus the SCS corals appear to conform to the control of annual SST on average calcification rates that characterises many Indo-Pacific reefs. Note that these analyses are based on the 1960 to 1990 base period used in earlier studies (e.g. Lough 2008).

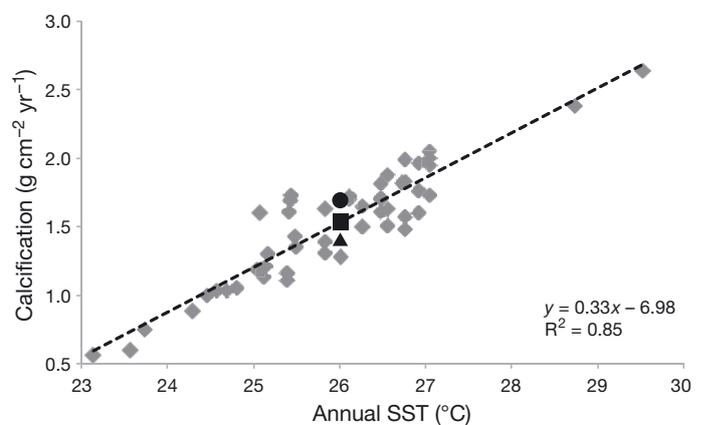


Fig. 5. Scatterplot based on 1961 to 1990 average data, for calcification vs. annual average sea surface temperature (SST) for 50 Indo-Pacific *Porites* sites (from Lough 2008; grey diamonds) and associated significant linear regression. Also shown are South China Sea (SCS) coral averages: black circle = *P. lobata*, black triangle = *P. lutea* and black square = average of all 16 SCS cores

Variation in growth characteristics through time

In this section we consider what, if any, variations in growth characteristics have occurred in the SCS coral over time. We present growth anomalies (with respect to the 1948 to 2001 average) for the period 1923 to 2002, for which 12 or more cores provided data (i.e. $\geq 75\%$ of cores). Over this period, the average time series for the *P. lobata* and *P. lutea* cores showed similar temporal variations and were significantly correlated at the 1% level (after correcting the degrees of freedom for autocorrelation) for extension ($r = 0.49$) and calcification ($r = 0.45$), but not for density ($r = 0.23$). The following analyses were therefore based on the combined 16-core average time series. The time series showed significant persistence (as measured by the lag 1 autocorrelation function, ACF) which was highest for density (ACF = 0.87) and lower for linear extension and calcification (ACF for both variables = 0.48).

Before considering the temporal variations in growth characteristics, we examined the variations in the thermal environment of the SCS over the study period, 1923 to 2002 (Fig. 6), based on annual average, annual maximum and annual minimum SST from the HadISST data set (Rayner et al. 2003). Significant persistence was only evident in annual SST (ACF = 0.27) and not in annual maximum (ACF = 0.01) or annual minimum SST (ACF = 0.17). Annual average SST significantly warmed over the period 1923 to 2002 (Fig. 6a) at 0.05°C per decade, with the warmest temperatures occurring in the 1960s and 1970s. There was no significant warming of maximum SST (Fig. 6b), in contrast to minimum SST (Fig. 6c), which warmed 0.13°C per decade but with the warmest SST in the 1970s.

Over the period 1923 to 2002, there was no significant linear trend in any of the 3 growth variables (Fig. 7; cf. original time series in Fig. S3; and complete anomaly time series in Table S1 in the Supplement). There was, however, marked de-

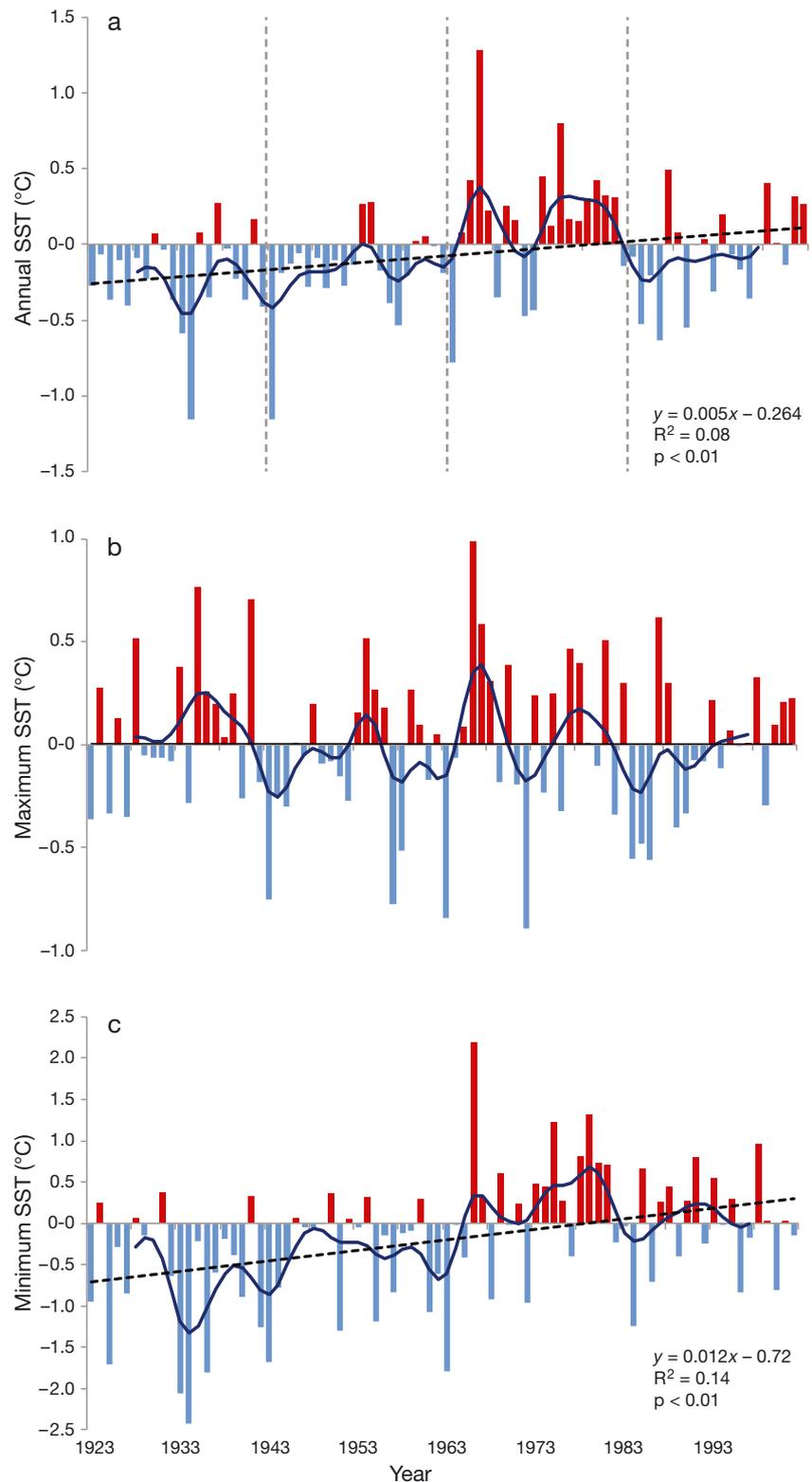


Fig. 6. Anomalies ($^\circ\text{C}$ from 1948 to 2001 average) for 19.5°N , 110.5°E for (a) annual average, (b) annual maximum and (c) annual minimum sea surface temperature (SST) for the period 1923 to 2002. Significant linear regressions are also shown. The vertical dashed lines separate four 20 yr periods (see Table 3)

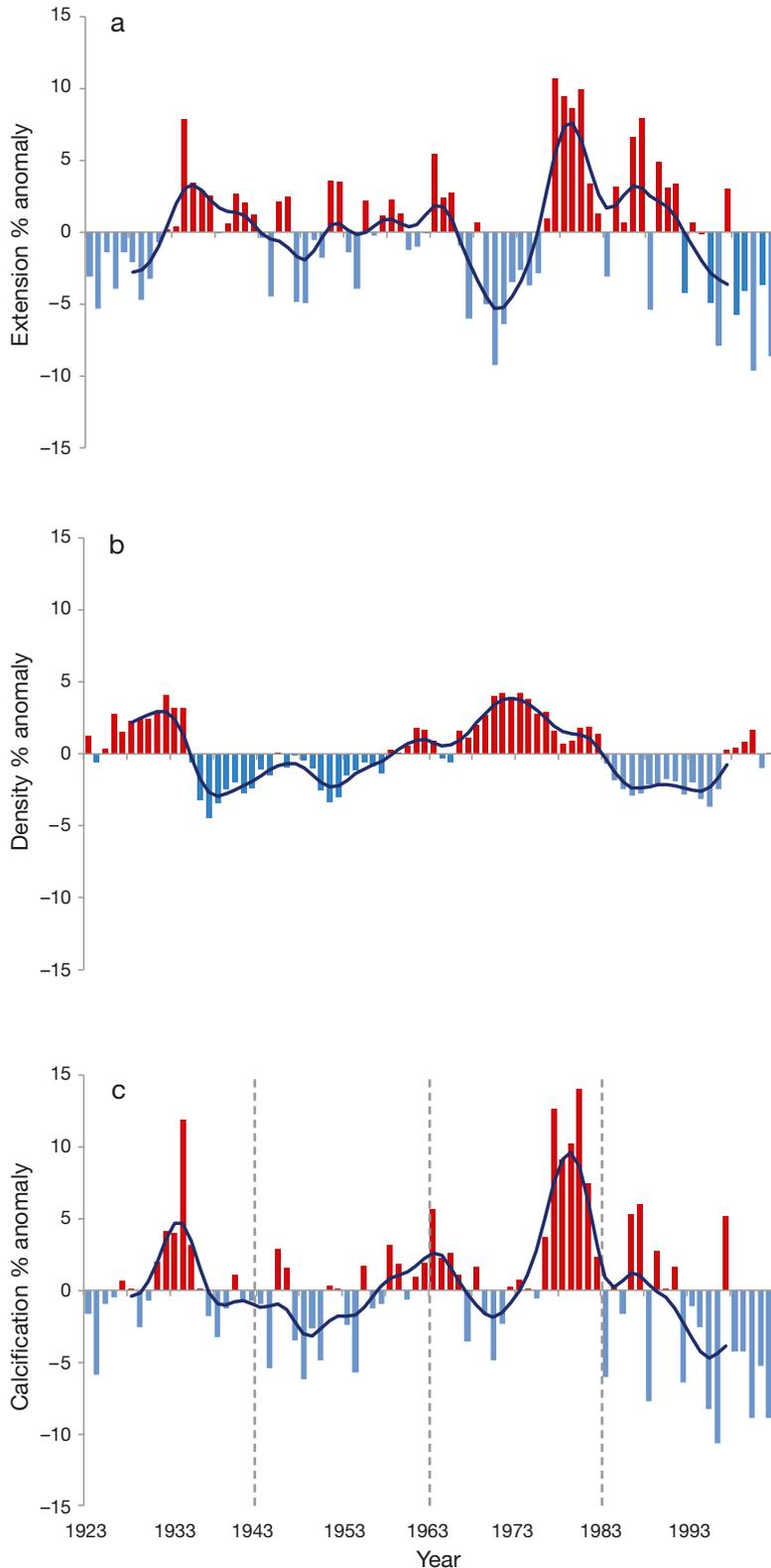


Fig. 7. Anomalies (% from 1948 to 2001 average) for (a) linear extension, (b) density and (c) calcification of *Porites* spp. coral for the period 1923 to 2002. The vertical dashed lines separate four 20 yr periods (see Table 3)

cadal variability in linear extension (Fig. 7a) and calcification (Fig. 7c) rates, with both showing highest values (+10–15% of 1923 to 2002 average) in the late 1970s to early 1980s followed by a substantial decline (~10%) in the most recent years of record. The latter period also coincides with lower skeletal density.

Over the period 1923 to 2002, density was not significantly correlated with extension ($r = -0.20$, $p = 0.19$) or calcification ($r = 0.29$, $p = 0.06$), and extension and calcification were significantly positively correlated ($r = 0.87$, $p < 0.01$).

We also examined the SST and growth time series for significant differences between four 20 yr periods (Table 3). These 20 yr periods were selected on the basis that annual calcification rate (Fig. 7c) showed a significant decrease (based on maximum t -value between successive 20 yr periods) between 1963–1982 and 1983–2002 and a significant increase between 1943–1962 and 1963–1982. Annual and minimum SST significantly warmed from 1943–1962 to 1963–1982. There was also a significant increase in density and calcification between these 20 yr periods. From 1963–1982 to 1983–2002, there was no significant change in SST, but both density and calcification significantly decreased.

DISCUSSION

Age effects on growth characteristics

We have presented new data on massive *Porites* annual growth rates for the northeastern coast of Hainan Island in the SCS. We found strong evidence in this data set for an age-related artefact in skeletal density (decreasing through time) and linear extension (increasing through time) but no obvious effect on calcification rate. Thus, a young colony tends to produce a skeleton of higher density but with lower linear extension rates than the same colony when older. This could be a strategy, which appears to stabilise after ~40 to 50 yr, of the young, small *Porites* colony to avoid dis-

Table 3. Differences in average sea surface temperature (SST, °C) and growth characteristics (%) between four 20 yr periods. Differences in **bold** are significant at the 5% level based on a *t*-test for differences between means (Mitchell et al. 1966)

Period	Annual SST	Maximum SST	Minimum SST	Linear extension	Density	Calcification
(1943–1962) to (1923–1942)	+0.04	–0.16	+0.31	–0.19	–0.98	–1.35
(1963–1982) to (1943–1962)	+0.34	+0.14	+0.59	+1.07	+2.83	+4.04
(1983–2002) to (1963–1982)	–0.23	–0.08	–0.25	–1.96	–3.60	–5.78

lodgement, especially in high-energy environments. It is also noteworthy that this age-related artefact does not appear to affect the calcification rate—thus, the coral appears to attempt to balance, throughout its lifetime, the complementary skeletal growth characteristics of skeletal density and linear extension rate to achieve an optimum calcification rate given ambient environmental conditions (e.g. average annual SST). Our evidence from *Porites* colonies in the SCS supports earlier studies (e.g. Lough 2008, Lough & Cooper 2011) and suggests that age-related effects should be considered, and corrected for when present, when examining long-term trends in massive coral growth rates. This becomes especially important in an era of rapid environmental change in tropical coral reef environments, so that erroneous conclusions are not reached about the nature and causes of recent growth trends. We note that in the companion field of dendroclimatology, it is routine to detrend tree-ring time series, as younger trees produce wide annual rings which progressively decrease in width with tree age (Fritts 1976).

Species differences in growth characteristics

We also found significant differences in average growth characteristics between *P. lutea* and *P. lobata* coral cores. *P. lobata* cores had significantly higher linear extension and calcification rates and significantly lower skeletal density than *P. lutea* cores. There was no significant difference in the depth of the living tissue layer between the 2 species. These results contrast with an earlier study of massive *Porites* on the Great Barrier Reef, Australia (Lough & Barnes 1992), which found no significant differences in growth characteristics among 4 massive *Porites* species. Since this earlier study, little attention has been paid to the species of massive *Porites* used in long-term growth studies, and coral samples are commonly referred to simply as *Porites* spp. (e.g. Carilli et al. 2012, Cooper et al. 2012, Tanzil et al. 2013). Temporal variations in the 2 species considered here were significantly correlated, suggesting

that they are responding in a similar manner to environmental variations. Species differences (if ubiquitous) could, however, compromise comparisons of average growth characteristics from different reef environments, and it would be prudent in future studies to identify *Porites* to the species level, where possible.

Average characteristics and Indo-Pacific model

Average annual SST exerts a strong control on average *Porites* linear extension and calcification rates (Lough & Barnes 2000, Lough 2008). This significant linear relationship, based on multiple reef sites throughout the Indo-Pacific, can also be used to test whether *Porites* from different reefs are performing as expected (Lough & Cantin 2014, Manzello et al. 2014). Comparison of average growth characteristics for the SCS cores showed, as found in several earlier studies with *Porites* (reviewed in Lough & Cooper 2011), that average linear extension varies inversely with average skeletal density and that linear extension rate is most strongly contributing to average and temporal variations in calcification rate. Average growth characteristics for the SCS *Porites* also closely fit with the general Indo-Pacific relationship between average calcification rate and average SST (see Lough & Cantin 2014). Thus, these corals appear to be calcifying at the rate expected given average SST over the period 1961 to 1990, suggesting that average SST is a primary driver of the observed average calcification rates.

Variations in growth characteristics through time and possible causes

We also examined temporal variations in growth characteristics over the period 1923 to 2002, for which ≥75% of cores contributed data. Over this period, annual average and annual minimum SST off northeastern Hainan island significantly warmed by 0.05°C and 0.12°C per decade, respectively. There

was no significant warming of annual maximum SST. For the tropical oceans (30° N to 30° S) over the same time period, annual and maximum SST warmed by 0.04°C per decade and annual minimum by 0.05°C per decade (Lough 2012). Thus annual SST in the SCS warmed at a similar rate to global tropical SST, annual maximum SST at less than the global tropics and annual minimum SST at about twice the rate of the global tropics. However, warming of annual and annual minimum SST in the SCS was not monotonic (see Fig. 6). Most of the warming (significant) occurred between 1943–1962 and 1963–1982 with a slight (but not significant) cooling between 1963–1982 and 1983–2002. Both skeletal density and calcification rate significantly increased (by ~3–4%) with the significant mid-20th century SST warming. Thus, this increase in calcification rate may have been a response to warming SST, as noted elsewhere (Lough & Barnes [2000] for the Great Barrier Reef; Cooper et al. [2012] for high-latitude reefs off Western Australia).

For the most recent 20 yr period of record, however, the SCS *Porites* showed a significant decline in calcification rate from the previous 20 yr. Over this period, SST did not continue to warm and even slightly cooled. Thus, in the absence of a temperature driver, what other factor(s) could have contributed to the recent significant decline in SCS skeletal density and calcification rates? A possible driver of the change since 1982 is local change in water quality, which is a known stressor of corals and coral reefs (Fabricius 2005), due to rapid expansion of aquaculture (shrimp and fish) on adjacent coastal lands (Shengli & Qinying 1999, Páez-Osuna 2001). Coastal land areas adjacent to the coral reef sites are now extensively covered by aquaculture ponds (see Fig. 2 in Herbeck et al. 2013) which discharge untreated effluent directly into coastal waters. The area covered by aquaculture ponds (both freshwater and seawater) for the Qionghai city region increased dramatically from the 1970s to the present (Fig. 8).

Although no continuous time series of water quality metrics are available for the region, recent studies (based on measurements made in 2007 and 2008) have demonstrated the impact of aquaculture ponds in northeastern Hainan Island (including Qingge) on adjacent coastal waters. These show clear signs of eutrophication, including high concentrations of dissolved inorganic nitrogen, carbon, phosphate and chl *a* (Herbeck et al. 2013). Those authors also reported levels of total suspended matter (TSM) up to 42 mg l⁻¹, inorganic nitrogen up to 40 µm and phosphate up to 3 µm. These values compare with the

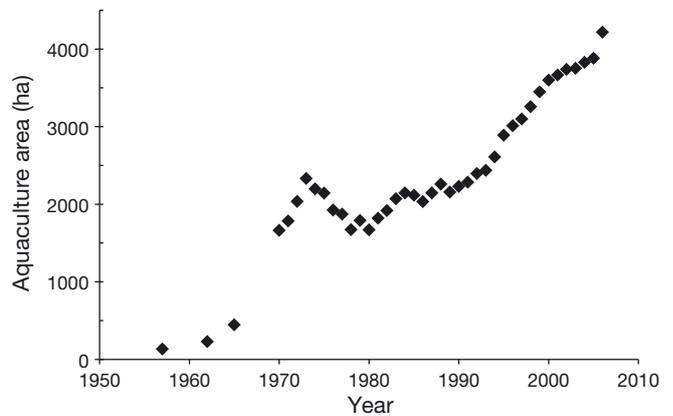


Fig. 8. Area (ha) of aquaculture (freshwater and seawater) for the Qionghai city region, 1957 through 2006 (Statistical Bureau of Hainan Province 2002, 2007)

upper limits typical for coral reefs of TSM < 10 mg l⁻¹ (Rogers 1990), inorganic nitrogen ~3 µm and phosphate of ~0.5 µm (Kleypas et al. 1999). In addition, the total export of aquaculture effluent and nitrogen loadings at Qingge is >50-fold higher than at a site to the north (Yelin) which has had little development of pond aquaculture (Herbeck & Unger 2013). These indications of poor water quality are attributable to aquaculture effluent being released directly into coastal waters which bathe the fringing reefs such as Qingge and Oucun. This degraded water quality has had a measurable impact on northeastern Hainan Island seagrasses (Herbeck et al. 2014) and coral reef community structure (Roder et al. 2013). There is also historical evidence, from a sediment core to the north of our study sites, that changes in coastal land use over the past 40 yr (from predominantly mangroves to aquaculture ponds) have clearly impacted the marine environment (Bao et al. 2013). We therefore suggest that the changes in massive *Porites* growth since 1923 documented in this study may represent an initial response of increasing calcification as SST warmed (as observed on the Great Barrier Reef, Lough & Barnes 2000) followed by a decline in calcification rate since the early 1980s due to eutrophication of coastal waters as a result of the rapid expansion of aquaculture ponds adjacent to the fringing reefs. Although the evidence is circumstantial, earlier studies have demonstrated that changes in reef water quality as a result of changing land use can severely impact coral reefs and reduce growth rates (e.g. Tomascik & Sander 1985, Fabricius 2005, Guzman et al. 2008, D'Angelo & Wiedenmann 2014). Chronic local anthropogenic stressors can also suppress recovery of normal growth rates after acute stresses such as coral bleaching (e.g. Carilli et al. 2009).

CONCLUSIONS

Coastal coral reef ecosystems of northeastern Hainan Island are not immune from globally and locally induced changes to the marine environment as a result of human activities. Our findings provide new evidence of the possible impact (slowed coral calcification) of rapid changes in land use on China's coral reef ecosystems which has been associated with widespread loss of coral cover and changes in coral reef community structure (Hughes et al. 2013, Roder et al. 2013). Improvements in land management practices (as recommended by Chou 2010) and removal of anthropogenic stresses can lead to some recovery of these valuable marine ecosystems (Zhao et al. 2014). To test whether eutrophication is the primary driver of the decrease in calcification rates after 1982 reported here, it would be informative to analyse growth records in coral cores from sites unaffected by aquaculture and also update records through to the present to determine whether the observed decline in calcification rates has been maintained.

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