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Skeletal Growth Rates in *Porites lutea* Corals from Pulau Tinggi, Malaysia

Chai Kee Ong [1], Jen Nie Lee [1,*] and Jani Thuaibah Isa Tanzil [2]

[1] Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Nerus 21030, Terengganu, Malaysia; ongchaikee@gmail.com
[2] St. John's Island National Marine Laboratory, Tropical Marine Science Institute, 18 Kent Ridge Road, Singapore 119227, Singapore; jani.tanzil@nus.edu.sg
* Correspondence: jennie@umt.edu.my

Abstract: Skeletal records of massive *Porites lutea* corals sampled from reefs around Malaysia have previously shown average decadal declines in growth rates associated with sea warming. However, there was a variability in growth declines between sites that warrant the need for investigations into more site-specific variations. This study analyzed decade-long (December 2004–November 2014) annual growth records (annual linear extension rate, skeletal bulk density, calcification rate) reconstructed from five massive *P. lutea* colonies from Pulau Tinggi, Malaysia. Significant non-linear changes in inter-annual trends of linear extension and calcification rates were found, with notable decreases that corresponded to the 2010 El Niño thermal stress episode and a pan-tropical mass coral bleaching event. Coral linear extension and calcification were observed to return to pre-2010 rates by 2012, suggesting the post-stress recovery of *P. lutea* corals at the study site within 2 years. Although no long-term declines in linear extension and calcification rates were detected, a linear decrease in annual skeletal bulk density by ≈9.5% over the 10-year study period was found. This suggests that although coral calcification rates are retained, the skeletal integrity of *P. lutea* corals may be compromised with potential implications for the strength of the overall reef carbonate framework. The correlation of coral calcification rates with sea surface temperature also demonstrated site-specific thermal threshold at 29 °C, which is comparable to the regional thermal threshold previously found for the Thai-Malay Peninsula.

Keywords: sclerochronology; calcification rate; linear extension rate; skeletal density; sea surface temperature; thermal stress

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1. Introduction

As corals calcify over time, they construct incremental layers of skeleton. Periodicities in these layers can provide a chronology for determining the age and growth patterns of coral [1]. Example of seasonal/annual periodicities present in coral skeletons include alternating high and low density (dark and light) bands visualized through X-radiography or alternating bright and dull luminescence bands visible under ultra-violet (UV) light [2,3]. These banding patterns serve as the basis of producing a growth timeline for the interpretation of various coral skeletal biogeochemical records used to reconstruct historical growth rates or environmental changes [4]. For example, coral skeletal records have been used to study long-term changes in growth rates and their relationship with various environmental factors (sea surface temperature, wave energy, depth gradient, rainfall, river runoff, etc.) [5–10].

Along the coast of Thai-Malay Peninsula, the most recent and largest-scale coral skeletal growth study involved reconstructing decades-long growth rates of *Porites* from a total of six locations, four of which were in Malaysia [10]. Based on analyses of 70 cores, previous study [10] revealed a regional decline in calcification rate (−18.6%), skeletal linear extension rate (−15.4%), and skeletal bulk density (−3.9%) over the period 1980–2010 that were associated with sea warming. However, there were location-specific variation in temporal growth trends found, where changes in calcification rates varied from not significant at Port Dickson to a decline of 21.57% at Pulau Payar [10]. In a related study [11], site-specific periodicities in density and luminescence banding patterns in the *Porites* corals were also found. These studies strongly indicate that the skeletal records in *Porites* around Peninsular Malaysia can be highly variable and dependent on site-specific environmental conditions [10,11].

As a follow-on to previous studies [10,11], the current study aims to investigate a temporal variation for the period December 2004–November 2014 (10 years) in skeletal growth rates of *Porites lutea* from Pulau Tinggi, an island off the southeastern coast of Peninsular Malaysia. Correlations between skeletal growth rates with sea surface temperature (SST) were also explored to identify potential of SST influence on the coral at this study site.

2. Materials and Methods

2.1. Study Area

Pulau (meaning "island" in Malay) Tinggi is one of 13 islands gazetted under Sultan Iskandar Marine Park [12]. The island is located ≈14 km off the southeastern coast of Peninsular Malaysia and ≈64 km from the Endau River (Figure 1a), which is one of the largest rivers in the southeastern coast of Peninsular Malaysia with a total discharge rate of ≈393 $m^3\ s^{-1}\ year^{-1}$ for the period December 2004–November 2014 [13]. Pulau Tinggi with a total area of 1524.18 hectares has tropical rainforest hills up to 600 m and several small rivers that flow from the hills to coastal area [14]. Pulau Tinggi is situated in the South China Sea and has a monsoonal climate where the island experiences heavy rainfall with strong northeasterly winds during the northeast monsoon (≈November–March), and drier weather with weaker southwesterly winds the during southwest monsoon (≈May–September) [15,16]. The coastal waters around Pulau Tinggi have relatively low sedimentation rate (1.5–5.1 mg $cm^2\ day^{-1}$) [17], and the reefs around Pulau Tinggi are generally in good condition with average live coral coverage of ≈59% [18].

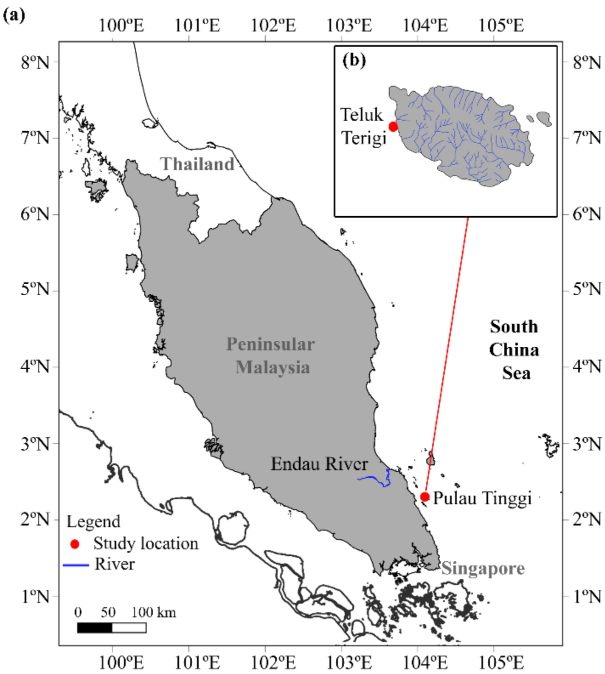

Figure 1. Map shows (**a**) Pulau Tinggi located off the southeastern coast of Peninsular Malaysia with (**b**) the sampling site at Teluk Terigi.

2.2. Coral Sampling and Processing

Cores from a total of five *P. lutea* coral colonies were sampled in August 2015 using a pneumatic drill fitted with a 5 cm diameter coring barrel [10]. All colonies sampled were from a depth of ≈2.5 m at mid-tide from the site Teluk Terigi (02°18.125′ N, 104°05.646′ E), a ≈50 m stretch of reef along the western coast of Pulau Tinggi (Figure 1b). All colonies sampled were 0.5–1 m in diameter in size, and core holes were plugged using marine epoxy to allow polyps recolonization of the removed surface. Of the five colonies sampled, two were previously stained with Alizarin Red S on 6 April 2014 and were used to verify the timing of banding patterns in the coral skeleton. The coral cores were cut into ≈7 mm thick slices and soaked in a 3–7% sodium hypochlorite (NaOCl) solution for 24–48 h to remove coral tissue and other surficial organics [19], ultrasonic cleaned with milli-Q water, and then air-dried prior to analyses.

2.3. Sclerochronology

Cleaned coral slices were scanned through a spectral luminescence scanning technique (SLS) using an X-ray fluorescence core scanner (Avaatech, Dodewaard, Netherlands) equipped with a long wavelength (≈365 nm) UV light source [11,20,21]. Based on the position of the Alizarin Red S stain line and previous banding patterns ascertained previously [11] for reefs in proximity to Pulau Tinggi, we defined annual growth for these coral samples as a pair of bright and dull luminescent bands measured from the onset of a bright luminescent band (≈December) to the adjacent onset of bright luminescent band. The annual linear extension rate (cm year^{-1}) was measured as the width of each annual growth. Skeletal bulk densities were analyzed using digitized X-ray images [11,22]. Annual calcification rate (g cm^{-2} year^{-1}) was calculated as a product of linear extension rate and skeletal bulk density [23]. No annual growth data was obtained from broken sections or if discoloration or boring organisms were noted. The annual coral skeletal growth of linear extension rate, skeletal bulk density, and calcification rate for the study period December 2004–November 2014 were obtained from all five coral cores.

2.4. Sea Temperature Data

Gridded monthly-averaged SST was obtained from the Integrated Global Ocean Services System Products Bulletin (IGOSS) Reyn_SmithOlv2 [24] for a 1° grid area (2°30′ N, 104°30′ E) covering the study site. Inter-annual variations of SST were obtained with the average from every twelve months data for the study period December 2004–November 2014.

2.5. Statistical Analysis

Inter-annual trends in skeletal growth rates and their relationships with SST were examined with generalized additive mixed-effects models (GAMM) that can accommodate both linear and non-linear regressions [25]. In these regression models, years or SST were included as fixed effects, and individual observations (data from five cores) were accounted for random effects [11]. The models were tested by applying different smoothing splines on fixed effects, and the best fit models were selected based on minimum Akaike Information Criterion (AIC) [26]. These models also interpreted with likelihood-ratio based pseudo-R-squared (R_LR^2) to measure the variance explained by fixed effects. All analyses were done using packages 'mgcv' [26], 'nlme' [27], and 'MuMIn' [28] through statistical program R version 1.4.1717 [29].

3. Results

3.1. Inter-Annual Variations in SST

Annual SST was presented with average (±S.E.) from every twelve months data (Figure 2; Supplementary Material Table S1). Average annual SST for the 10-year study period (2005–2014) was 28.97 ± 0.08 °C, and it ranged from a minimum of 28.68 ± 0.24 °C in 2011 to maximum of 29.44 ± 0.26 °C in 2010.

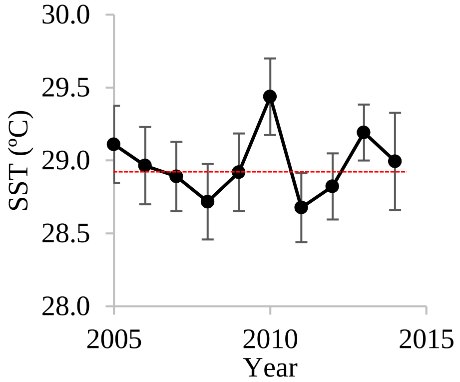

Figure 2. Plots show annual sea surface temperature (SST) with average (±S.E.) from every twelve months data for the period December 2004–November 2014 and average annual SST for the 10-year indicated with a dotted red line drawn from IGOSS data [24].

3.2. Inter-Annual Variations in Coral Skeletal Growth Rates

We found significant non-linear variations ($p < 0.05$) in linear extension (LE) and calcification (CALC) rates within the 2005–2014 study period. Annual linear extension and calcification rates averaged 2.18 ± 0.04 cm year^{-1} and 2.46 ± 0.05 g cm^{-2} year^{-1} respectively, dipping to an average of 1.88 ± 0.15 cm year^{-1} and 2.01 ± 0.08 g cm^{-2} year^{-1} in 2010. Decreases in growth seen in 2010 were driven largely by reductions of linear extension and calcification rates by 14.7% and 25.6% respectively over the years (Figure 3a,b, Table S1). Post 2010, average linear extension and calcification rates increased to 2.37 ± 0.14 cm year^{-1} and 2.56 ± 0.15 g cm^{-2} year^{-1} by 2012, which were comparable to the pre-2010 rates (i.e., average LE of 2.17 ± 0.05 cm year^{-1} and CALC of 2.52 ± 0.09 g cm^{-2} year^{-1}) (*t*-test, p = 0.25 and 0.83). Annual skeletal bulk density over the 10-year study period showed a significant linear decline ($p < 0.01$) by 9.46% from 1.23 ± 0.04 g cm^{-3} in 2005 to 1.11 ± 0.02 g cm^{-3} in 2014 (Figure 3c, Table S1). Overall, variations in annual calcification rates were driven by changes in linear extension rates and not skeletal bulk density (Supplementary Material Figure S1).

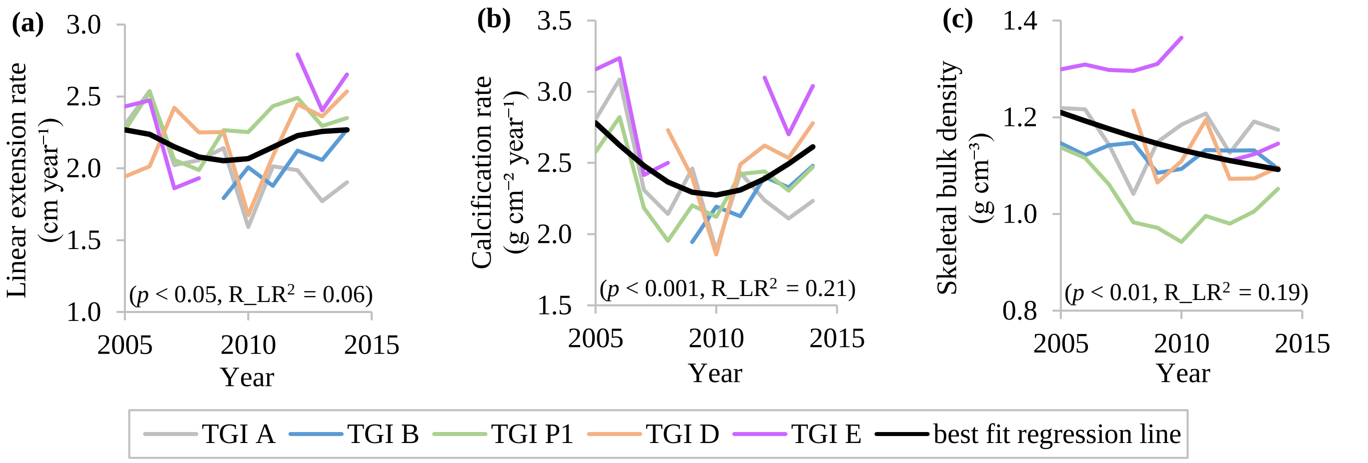

Figure 3. Plots show annual coral skeletal growth of (**a**) linear extension rate, (**b**) calcification rate, and (**c**) skeletal bulk density for five coral cores (colored lines) and the estimated trend with best fit regression (black lines) for the period December 2004–November 2014. The significances of the regression line at $p < 0.001/0.01/0.05$ and R_LR^2 are shown in brackets. 95% confidence intervals of regression lines were not shown for clarity of plots.

3.3. Relationships between Coral Skeletal Growth and SST

Relationships between coral skeletal growth rates and SST were also examined with regression models of GAMM (Figure 4; Supplementary Material Table S2). Non-linear relationships with rapid declines beyond the thermal threshold were observed for a linear extension rate at 28.96 °C ($p < 0.05$, $R\_LR^2 = 0.13$) and calcification rate at 28.99 °C ($p < 0.01$, $R\_LR^2 = 0.17$). A weaker non-linear relationship between the annual skeletal bulk density and SST was also found ($p < 0.05$, $R\_LR^2 = 0.06$), where the highest average skeletal density occurring at 29.19 °C (Figure 4).

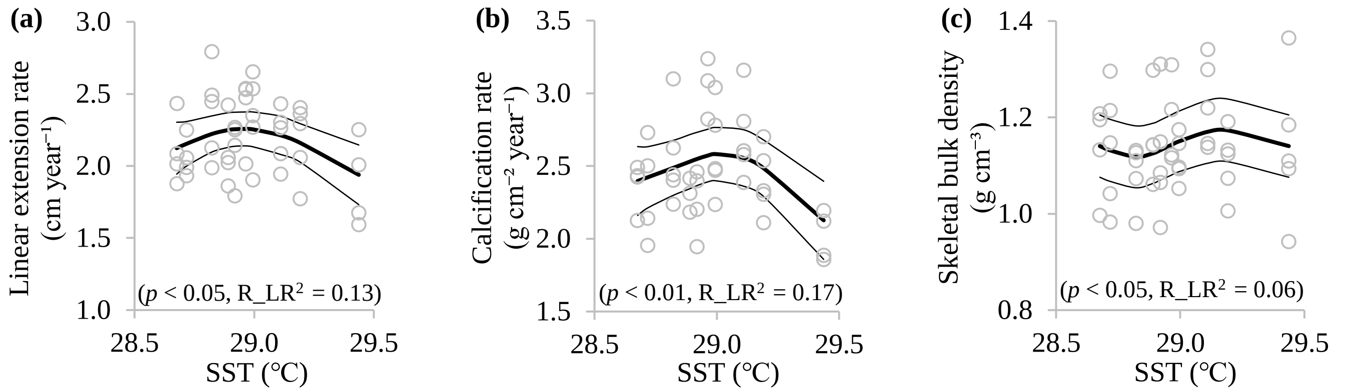

Figure 4. Plots show relationships for (**a**) linear extension rate, (**b**) calcification rate, and (**c**) skeletal bulk density with SST. The significances of relationships at $p < 0.01/0.05$ and R_LR^2 are shown in brackets. Gray circles: annual data, black lines: best fit regression line with 95% confidence intervals.

4. Discussion

The current study found that the calcification rates for *P. lutea* corals from Pulau Tinggi to be high and comparable with previously recorded growth rates for massive *Porites* corals from reefs along the east coast of Peninsular Malaysia (Pulau Redang, Pulau Tioman) and Phuket, Thailand (Table 1). Notwithstanding the different lengths of growth records, calcification rates at Pulau Tinggi were also notably higher than those found for higher latitude reefs (Nansha Island, Great Barrier Reef and Western Atlantic) and an urbanized reef (Singapore) [7,10,30,31] (Table 1).

Table 1. Coral skeletal growth rates (mean ± S.E.) from different reef location in Southeast Asia and other region.

Reef Location	Years	Linear Extension Rate (cm year^{-1})	Calcification Rate (g cm^{-2} year^{-1})	Skeletal Bulk Density (g cm^{-3})
Pulau Tinggi [this study]	2005–2014	2.18 ± 0.04	2.46 ± 0.05	1.14 ± 0.01
Pulau Tioman [10]	1980–2010	1.72 ± 0.30	2.24 ± 0.23	1.31 ± 0.13
Pulau Redang [10]	1980–2010	1.97 ± 0.22	2.32 ± 0.22	1.19 ± 0.06
Singapore [10]	1980–2010	1.66 ± 0.45	1.71 ± 0.33	1.13 ± 0.28
Phuket, Thailand [10]	1980–2010	2.08 ± 0.38	2.29 ± 0.29	1.12 ± 0.14
Great Barrier Reef [7]	1934–1982	1.48 ± 0.32	1.72 ± 0.36	1.17 ± 0.10
Western Atlantic [30]	1995–2006	0.37 ± 0.65	0.55 ± 0.12	1.49 ± 0.16
Nansha Island [31]	1716–2005	0.91 ± 0.26	1.30 ± 0.35	1.45 ± 0.15

The decade-long *P. lutea* coral growth records from Pulau Tinggi, Malaysia also revealed gradual decline inter-annual changes in all growth parameters. We found non-linear variations in linear extension and calcification rates with a significant decrease in average rates recorded in 2010. In 2010, a marine heatwave caused by an El Niño event increased SSTs throughout the tropical Pacific region. The average SSTs around Malaysia were reported to reach up to 31 °C in May 2010 [10]. Similar high SSTs were found for Pulau Tinggi at the same period (Figure 2). As a consequence of this thermal stress event, severe pan-tropical coral bleaching was reported [32], including in Malaysia, where bleaching rates of up to 90% were recorded along the east coast of Peninsular Malaysia, including for the reefs at Pulau Tinggi [33,34]. Therefore, the significant reductions in growth rates in 2010 found for the *P. lutea* corals at Pulau Tinggi are likely a consequence of the thermal-induced bleaching event. However, we noted that the decrease in average linear and calcification rates were largely driven by two out of the four corals where growth records extend throughout the 2010 period (Figure 3), suggesting variable responses by the *P. lutea* corals at Pulau Tinggi to the thermal stress event in 2010. This is consistent with studies reported at the Mesoamerican Barrier Reef [35], Great Barrier Reef [36], and Central Red Sea [37], where decreases in linear extension rates as reconstructed from coral skeletal records have been linked to past thermal stress events. However, such decreases in growth, and "stress bands", were not always present in all corals sampled from the same site, possibly reflecting differences in bleaching stress response between colonies [36].

Comparing the annual growth rates post-2010 (i.e., 2011 to 2014) to pre-2010 (i.e., average for 2005–2009), our study found that linear extension and calcification returned to pre-2010 rates by 2012. This indicates that coral growth rates were able to recover within ≈2 years following the 2010 stress event. This is a much faster rate than previously found from coral records Great Barrier Reef and Central Red Sea, which suggested the recovery of growth rates within 4 years following a severe bleaching event in 1998 [36,37]. We note that the number of coral cores used in the current study is relatively low (n = 5), and that more replicates will be needed to ascertain the impacts of the 2010 bleaching event on *P. lutea* growth both for rates of declines and recovery. However, our data showed that both linear extension rate and calcification were able to recover to pre-2010 rates within 2 years. The coastal waters around Pulau Tinggi generally experience low sedimentation rates [17] and good water quality [38] with a good percent of live coral cover on the reefs [18]. The lower local environmental stress experienced around Pulau Tinggi may have facilitated a relatively faster recovery rate of *P. lutea* corals from the 2010 thermal stress event at this site. Faster recovery rates at sites with lower environmental stressors have previously been found for *Montastraea faveolate* at the Mesoamerican Barrier Reef [35]. Similarly, *Porites* growth studies at the Great Barrier Reef and Central Red Sea also suggest that good water quality and lower environmental disturbances can improve coral's ability to recover from thermal stress events [36,37]. While there was a detected recovery of linear extension and calcification rates following the 2010 stress event, there was a significant linear decline in average annual skeletal bulk density by ≈9.5% over the 2005–2014 study period. The rate of decline in annual skeletal density found in the current study (≈1% per year) is 2–3-fold higher compared to rates previously found for reefs around the Peninsular Malaysia, i.e., Port Dickson (−0.34% year^{-1}) and Pulau Redang (−0.22% year^{-1}) for the period 1980–2010 [10]. As found in previous studies [39,40], variations in calcification rates for *P. lutea* at Pulau Tinggi were also mainly driven by linear extension rates rather than skeletal density. Although no long-term declines in linear extension and calcification rates were detected, the significant decrease in annual skeletal bulk density found here suggests that the skeletal integrity of *P. lutea* corals may be compromised with potential implications for the strength of the overall reef carbonate framework.

The thermal threshold of calcification rates (29.0 °C) found at Pulau Tinggi was comparable to that found for Pulau Redang (28.4 °C) and Pulau Tioman (28.8 °C)—two reefs >40 km from Pulau Tinggi (Figure 5), and below the regional thermal threshold for calcification (29.4 °C) reported by a previous study [10] for the Thai-Malay Peninsula (Figure 5). Our results add to evidence that there can be high site-dependent variability for thermal calcification thresholds, with the thermal threshold for Malaysia being much higher compared to those found for the Caribbean Sea (25.5 °C), Gulf of Mexico (23.7 °C), Great Barrier Reef (26.7 °C), Central Red Sea (30.5 °C), and Meiji Reef (27.2 °C) [31,41–43]. Although the current study also found a significant relationship ($p < 0.05$) between annual skeletal bulk density and SST, this relationship was weak ($R\_LR^2 = 0.06$), suggesting that SST may not the primary driver of variations in skeletal bulk density in *P. lutea* at Pulau Tinggi, and there could be an influence of other yet unaccounted for parameters (e.g., wave energy or nutrients as suggested by previous studies [10,11].

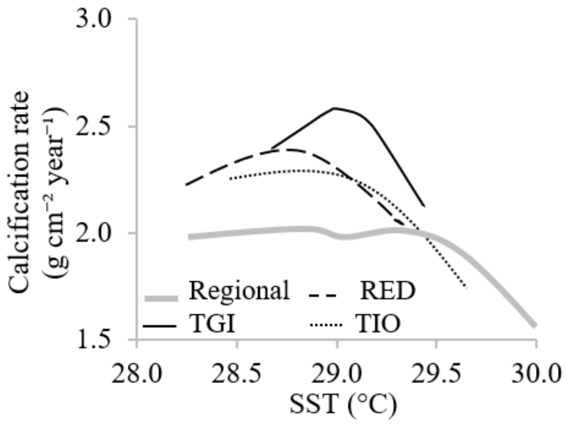

Figure 5. Plot shows comparison of relationships between calcification rate and SST with previous study [10]. Regional: Thai-Malay Peninsula, TGI: Pulau Tinggi, RED: Pulau Redang, TIO: Pulau Tioman.

5. Conclusions

The current study found non-linear trends in the annual linear extension rate and calcification rate for 10 years of coral skeletal growth in *P. lutea* from Pulau Tinggi. Reductions were noted during the 2010 El Niño event with such recovery able to achieve again normal growth within 2 years. The coral growth also correlated with SST, and the calcification rate demonstrated the site-specific thermal threshold at ≈29 °C, which is comparable to the regional thermal threshold previously reported for the Thai-Malay Peninsular [10]. While previous study on long-term temporal trend had provided an overview on how continuous SST warming affects the coral skeletal growth across reefs in the same region, the interpretation of short-term inter-annual trends in the current study helps to understand the resilience of a local reef to withstand past thermal stress events. As more coral growth responses have been revealed as a consequence of climate and environmental changes, continuous monitoring is necessary to enhance our knowledge for a better conservation and management of our coral reef ecosystem.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w14010038/s1, Table S1. Data for annual SST and coral skeletal growth rates (mean ± S.E.) over the period December 2004–November 2014. Table S2. Best fit GAMM selected to examine trends of annual skeletal growth rates over years and their relationships with SST. Figure S1. Plots show correlations between skeletal growth rates with the significances of relationships at $p < 0.05$ shown in brackets. Gray circles: annual data, black lines: linear regression.

Author Contributions: Conceptualization, J.T.I.T. and J.N.L.; methodology, J.T.I.T. and J.N.L.; software, C.K.O. and J.T.I.T.; validation, C.K.O.; formal analysis, C.K.O.; investigation, C.K.O.; resources, J.T.I.T. and J.N.L.; data curation, C.K.O.; writing—original draft preparation, C.K.O.; writing—review and editing, J.T.I.T. and J.N.L.; visualization, J.T.I.T. and J.N.L.; supervision, J.T.I.T. and J.N.L.; project administration, J.T.I.T. and J.N.L.; funding acquisition, J.T.I.T. and J.N.L. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

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