Growth Rates Analysis of *Porites* Corals from Nusa Penida, Bali

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Abstract. The annual growth of *Porites* coral is represented by a pair of high- and low-density bands. Environmental changes in the ambient waters influence the pattern of these annual density bands. Five colonies of *Porites* corals from Nusa Penida, Bali were investigated to analyze their annual linear growth rates using coral densitometry. From the analysis it was found that the annual linear growth rates of the colonies varied between 0.8924 to 1.0012 cm/yr. The trends of the colonies growth rates also varied. Two colonies showed a decreasing trend, while the others showed an increasing trend. The annual linear growth rates of most of the colonies were not influenced by sea surface temperature (SST); only one out of five colonies had a significant correlation with SST ($R = 0.66$, p-value < 0.05).

Keywords: *coral growth rates; densitometry; Nusa Penida; Porites; SST.*

1 Introduction

Nusa Penida was established as a marine protected area (MPA) in 2010, with an area of 20,057 hectares. It is part of the Coral Triangle (CT) region and has a highly diverse coral ecosystem, with around 296 species of corals and 576 species of reef fishes. As an MPA, complete data and information related to marine environment conditions are necessary to support the development of better MPA management. In line with this purpose, a study utilizing massive *Porites* corals was done to estimate their annual growth and analyze the relation with some climatological indices.

Porites is a common genus of coral with a worldwide distribution. It can grow for centuries and form massive colonies of several meters height [1,2]. The range of *Porites* lies largely in tropical areas [3,4]. Even though *Porites* has great importance within the ecosystem, there is a lack of data about the

Received September 18th, 2014, 1st Revision December 11th, 2014, 2nd Revision October 19th, 2015, Accepted for publication November 9th, 2015.
 ISSN: 2337-5760, DOI: 10.5614/j.math.fund.sci.2016.48.1.2

correlations between species and populations. The characteristics of the *Porites* species are hard to identify, as they vary considerably [5].

Porites growth involves an increase in both tissue and skeleton. Environmental controls on the growth of corals include seawater temperature [6-9], light [10], carbonate saturation state [11], water motion [12], water quality [13], and rising concentrations of athmospheric greenhouse gases [14].

Massive *Porites* corals are often used to predict past environmental conditions [15-17]. Corals record environmental history in their calcium carbonate skeletons [18-20]. A series of growth bands is created by the precipitation of calcium carbonate deposited on the skeleton during their growth [21,22]. Long-term dated histories of coral growth, density and calcification rates can be obtained by analyzing the patterns of annual high-density (HD) and low-density (LD) bands in massive coral skeletons produced during their growth [9,23].

Measurement of coral growth parameters, i.e. calcification, density and linear extension, are important for understanding what controls coral growth. Several studies have provided evidence of a recent decline in massive coral calcification rates that may be related to recent changes in sea surface temperature (SST) [24-27]. A study by Suharsono and Cahyarini [28] showed that the linear growth trends of *Porites* coral from different sites in Indonesia (i.e. Biak, Maumere and Natuna) showed different responses to changes in SST. A study on Seribu Island showed that offshore coral linear growth was more affected by SST than inshore coral linear growth from 1996 to 2005 [29].

Studies on determining coral growth have been done using densitometry [23,30] and computed tomography [25]. In this study we analyzed the annual linear growth of *Porites* corals from Nusa Penida, Bali using the Coral X-radiograph Densitometry System (CoralXDS) [30]. The results were correlated to SST.

2 Material and Methods

2.1 Study Site

Figure 1 shows the research location of Nusa Penida Island, including the two other smaller islands of Lembongan and Ceningan (8°38’-8°49’S and 115°25’-115°37’E). This group of islands is located 20 km off the south east coast of Bali Island and is part of Klungkung regency. The climate is much like Bali’s, with the rainy season from November to March and the dry season from April to October. The average temperature is 28-30 °C and annual precipitation is approximately 1,000 mm [31].

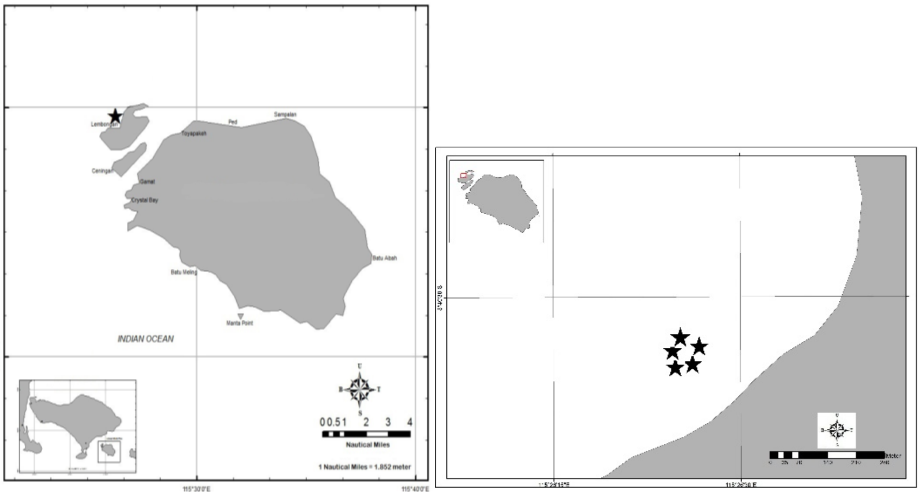

Figure 1 Coral site indicated by asterisk (left) and positions of cores (right).

2.2 Methods

Five *Porites* corals from Nusa Penida, Bali (NP1, NP2, NP3, NP4 and NP5) were used in this study. All cores were drilled from the top down to the bottom of the coral using a pneumatic drill powered by a scuba tank. The lengths of the 5 cores were different (NP1: 60 cm; NP2: 47 cm; NP3: 81 cm; NP4: 133 cm; and NP5: 75 cm). From the length of each of the cores we assumed different coral ages (the 5 corals each have a different living period). The coral cores were cut into 5 mm thick slabs. The coral slabs were then X-rayed (Figure 2) and the digital images were used as input for Coral XDS from the National Coral Reef Institute Nova South Eastern University Oceanographic Center (NSUOC) [32] to calculate the annual linear extension for each core [30]. In this approach, an X-ray image of the coral with scale in pixels per centimeter is required. It is widely accepted that 2 bands, HD and LD, represent 1 year of growth [33-36]. Thus we can determine the living period of a coral. The first combination of HD and LD quantities was defined as the linear extension over the year 2012, since the cores were drilled in March 2013 (assuming that the top of the core is the coral layer that grew in 2012). The analysis was continued further until the last HD and LD quantities of each core.

The cores were drilled from different colonies in one location north of Nusa Lembongan (indicated by an asterisk in Figure 1), with a distance between the colonies of about 5 meters. The area is a white sandy field, at a distance of about 700 meters from the shoreline and 5 meters in depth.

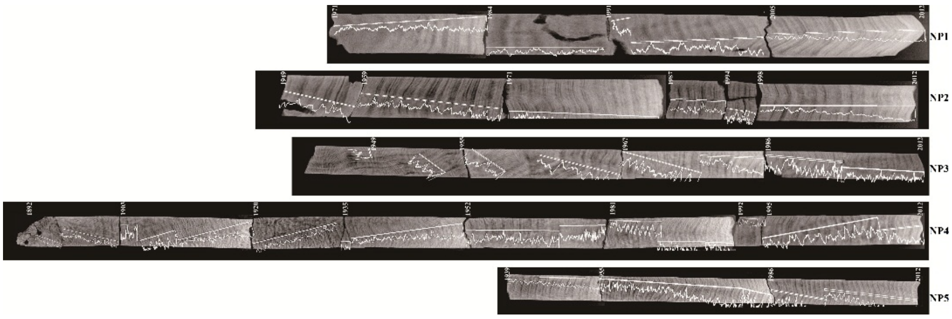

Figure 2 X-rays of five *Porites* coral cores from Nusa Penida (NP1, NP2, NP3, NP4 and NP5, respectively) and transect line for linear growth analysis (white line).

In order to observe the dependency of annual linear growth of corals on SST, data from Extended Reconstruction Sea Surface Temperature (ERSST) [37,38] were used. Furthermore, we also tried to analyze the relation between these annual growths and the El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) indices, since the study location is part of the area where the influence of these regional phenomena is significant.

3 Results and Discussions

The annual linear growth values of the 5 coral samples (NP1, NP2, NP3, NP4, and NP5) show ages ranging from 42 years (NP1) to 121 years (NP4). Table 1 shows the living periods of the coral colonies and the mean annual linear growth rates. The mean annual linear growth rates of the *Porite*s coral samples from Nusa Penida varied between 0.8607 and 1.0012 cm/yr.

Table 1 *Porites* Coral Mean Annual Linear Growth for NP1, NP2, NP3, NP4, NP5.

Core ID	Period	Mean annual linear growth rates ± sd (cm/year)	Slope	p-value
NP1	1971 - 2012	1.0012 ± 0.3058	+ 0.0026	0.5032
NP2	1949 - 2012	0.8607 ± 0.2549	+ 0.0028	0.1003
NP3	1949 - 2012	0.9489 ± 0.2866	- 0.0033	0.0880
NP4	1892 - 2012	0.9521 ± 0.2853	+ 0.0017	0.0220
NP5	1939 - 2012	0.9572 ± 0.2849	- 0.0003	0.8636

The mean linear growth rates of the 5 cores are 1.0012 ± 0.3058 cm/yr, 0.8607 ± 0.2549 cm/yr, 0.9489 ± 0.2866 cm/yr, 0.9521 ± 0.2853 cm/yr, 0.9572 ± 0.2849 cm/yr for NP1, NP2, NP3, NP4 and NP5, respectively. Meanwhile, the living periods of the cores are 42 years (1971-2012), 64 years (1949-2012), 121 years (1892-2012) and 74 years (1939-2012), respectively.

The linear growths of the 5 colonies of *Porites* can be so varied because they have different living periods. The living period can have an influence on the health of the coral and also on its resilience in responding to environmental changes. One way of determining a coral's responses is by looking at its annual growth.

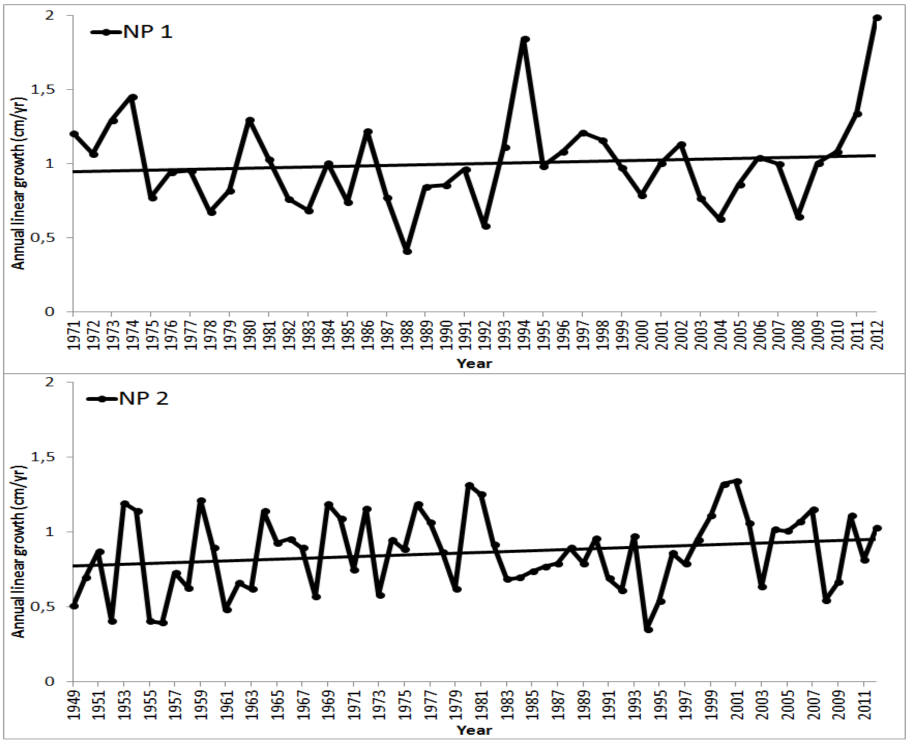

Figure 3 Variation of *Porites* coral annual linear growth and its linear trend for NP1 (1971-2012) and NP2 (1949-2012).

The analysis results show that during the period of 1949 to 1968, the annual growth rates of NP2 were slower than those of other massive corals, i.e. only 0.7664 cm/yr (Figure 3). This period significantly influenced the total annual linear growth of NP2. Since the 5 massive corals grew in very similar environmental conditions, with a distance between each colony of only around 5 meters, the lowest growth rates found in the NP2 core during this period could be due to its health.

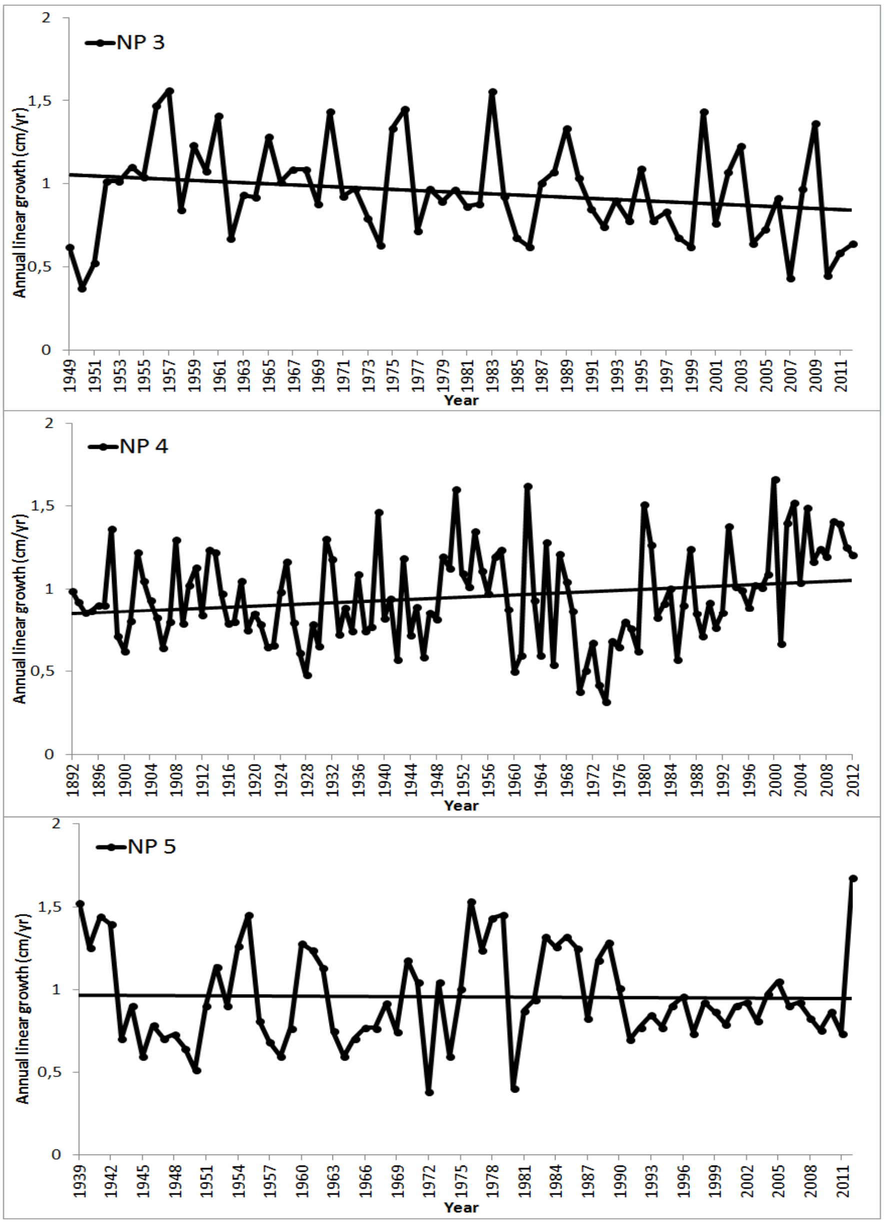

Figure 4 Variation of *Porites* coral annual linear growth rate and its linear trend for NP3 (1949-2012), NP4 (1892-2012) and NP5 (1939-2012).

Over the period of their growth, the mean annual linear growth rates of NP3 and NP5 show a decreasing trend (Table 1 and Figure 4), while for the remaining corals they show an increasing trend. However the p-value (Table 1) shows that only the increasing trend of NP4 (p-value < 0.05) is statistically significant, while the other corals show either an increasing trend (NP1 and NP2) or a decreasing trend (NP3 and NP5) that is not statistically significant (p-value > 0.05).

Since the shortest living period of the 5 *Porites* corals was found in the NP1 sample (42 years), the period from 1971 to 2012 was selected for further analysis. This analysis revealed that the mean annual linear growth rates of *Porites* coral from Nusa Penida varied between 0.8924 and 1.0012 cm/yr (Table 2). For the last 42 years, the mean annual linear growth rates of NP3 (Figure 5) and NP5 (Figure 6) show a decreasing trend, while the remaining samples show an increasing trend. Similar to the analysis results over the whole obtained period for each core, the p-values show that only the increasing trend of NP4 is statistically significant (p-value < 0.05).

Table 2 *Porites* Coral Mean Linear Growth and Correlation Between SST, NINO3.4, IOD and Linear Growth (95% Confidence Level), 1971-2012.

Core ID	Period	Mean annual linear growth rates ± sd (cm/year)	Slope	R value of SST vs linear growth	SST	p-value NINO3.4	IOD
NP1	1971 – 2012	1.0012 ± 0.3058	+ 0.0026	0.1400	0.5032	0.4334	0.0873
NP2	1971 – 2012	0.8924 ± 0.2367	+ 0.0011	0.0316	0.7222	0.6053	0.8793
NP3	1971 - 2012	0.9079 ± 0.2707	- 0.0053	0.2478	0.1235	0.5342	0.9439
NP4	1971 - 2012	0.9959 ± 0.3264	+ 0.0181	0.6594	0.000001	0.2582	0.9079
NP5	1971 - 2012	0.9768 ± 0.2784	- 0.0031	0.1300	0.3921	0.7901	0.1431

Extracting and plotting the SST data from ERSST for the time period of 1971-2012 in the study area showed an increasing trend. SST higher than 29 °C was found in the years 1998, 2005 and 2010 (indicated by shadow box in Figure 5 and 6) and these conditions coincided with lower annual linear growth rates. For example, the annual linear growth rates of NP1 in 2005, when the SST reached 29.23 °C was only 0.8623 cm/yr, while during 1977, when SST was around 27.84 °C, the annual linear growth was 0.9552 cm/yr. This indicates that natural factors, such as changes in SST, influence coral growth [24,25]. However, this pattern did not occur in all colonies. This means that the relationship between the growth rate of the coral and SST in Nusa Penida is weak or unclear. It is therefore likely that growth responses of the corals around Nusa Penida depend not only on SST but probably also on other parameters, such as nutrients, pH, salinity, and precipitation.

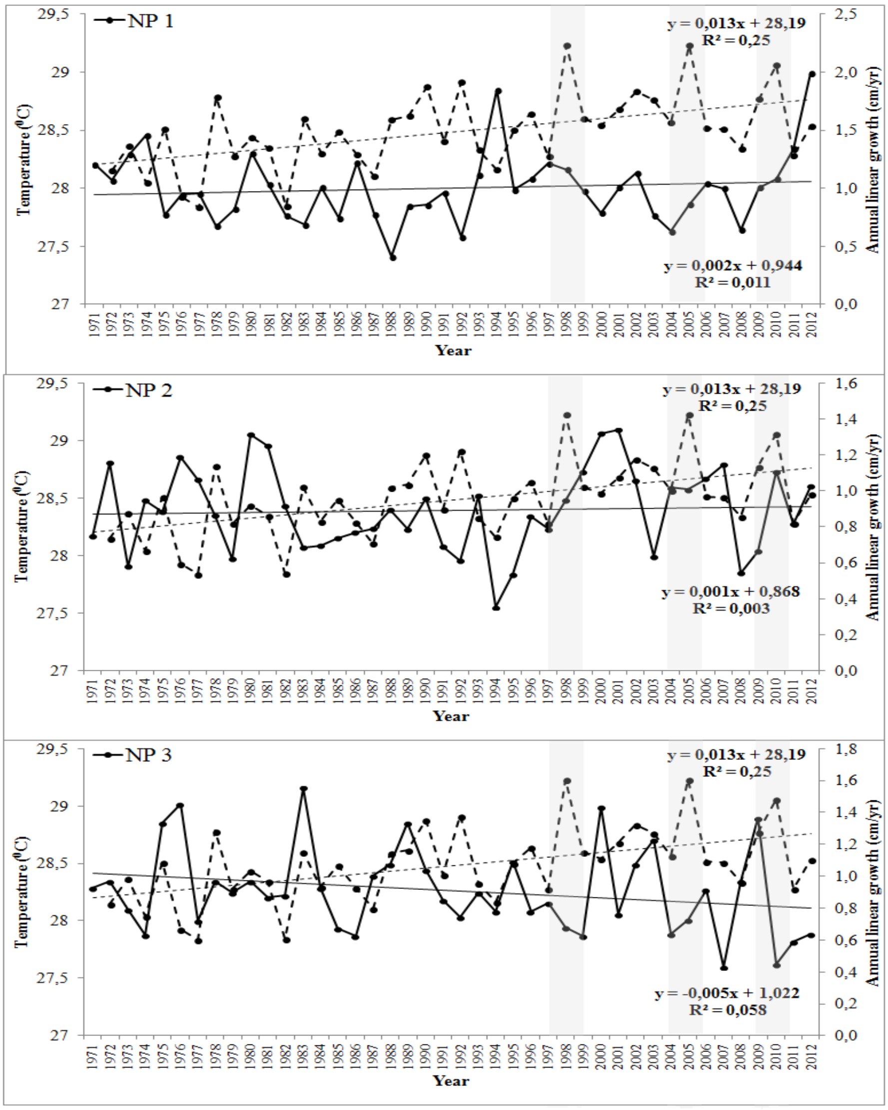

Figure 5 Comparison of annual linear growth rates of *Porites* coral from Nusa Penida (NP1, NP2 and NP3) and SST (dashed line) obtained from ERSST dataset.

The correlation between coral growth and temperature was considered with calcification rates repeatedly shown to increase with rising temperature, up to a maximum, and then to decrease slightly coinciding with further increases in temperature [37].

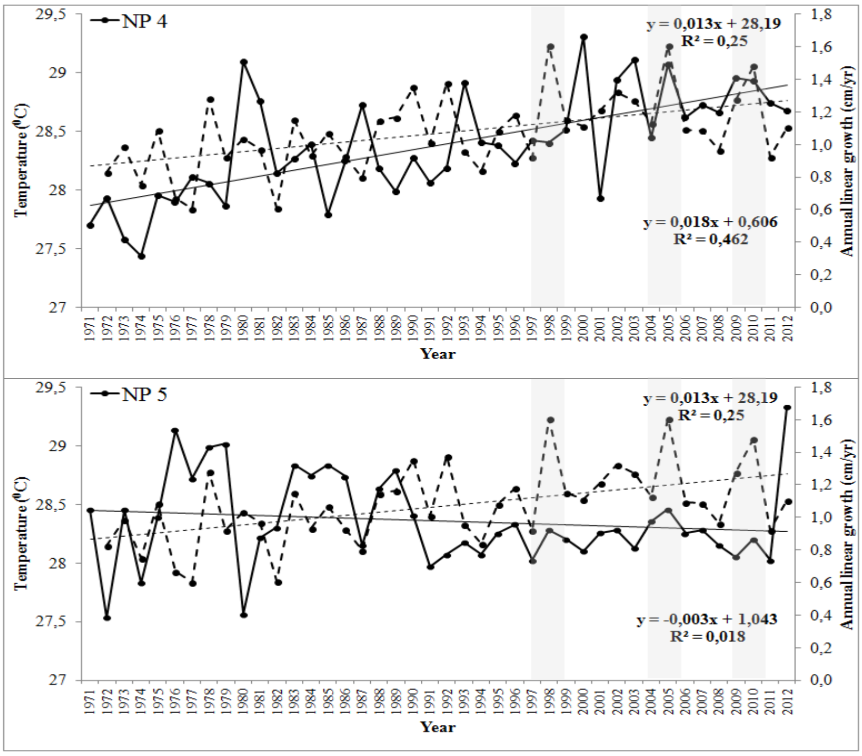

Figure 6 Comparison of annual linear growth rates of *Porites* coral from Nusa Penida (NP4 and NP5) and SST (dashed line) obtained from ERSST dataset.

A comparison of the annual linear growth rates and annual SST shows that for NP3 and NP5 an increase in SST coincided with a decrease in annual linear growth rate, but a different result was found for NP1, NP2, and NP4, where the increase of SST coincided with an increase in annual linear growth rate. This varied response requires further analysis in order to understand the influence of SST on the annual linear growth rates of *Porites* coral in Nusa Penida.

From the correlation analysis between the annual linear growth rates of Nusa Penida cores and the SST anomaly in the NINO3.4 region, we could not find any significant correlation values. Similar results were found when trying to correlate the annual linear growth rates with the IOD index. Further work is needed to understand this, since according to [38], based on an analysis of a core sample from Padang Bai (to the northeast of Nusa Penida), the Bali record evidently shows unique local influences in addition to the Indonesian-wide response to ENSO.

4 Conclusion

The mean annual linear growth rates of 5 *Porites* coral colonies from Nusa Penida, Bali for the time period of 1971 to 2012 (42 years), vary from 0.8924 to 1.0012 cm/yr. 3 *Porite*s colonies, i.e. NP1, NP2, and NP4, show an increasing growth trend, while the 2 other colonies (NP3 and NP5) show a decreasing growth trend. Comparing the annual linear growth rates with SST over the same period shows a high correlation coefficient between SST and annual linear growth with $R = 0.66$ only for the NP4 colony, of which the annual linear growth rates coincide with an increase in SST. On the other hand, comparing the annual linear growth rates with the ENSO and IOD indices did not give any significant correlation. It is suggested that local influences, such as precipitation, nutrient or food availability and salinity may have a more dominant influence on coral growth rate in this area.

Acknowledgements

We thank Eghbert Elvan Ampou, Dudi Prayudi, Suciadi Catur Nugroho and Nuryani Widagti for their field support and laboratory work; Iis Triyulianti, Abdul Rohman Zaky and Jejen Jenhar Hidayat for their discussion. Acknowledgements are also addressed to the Geotechnology Research Centre, Indonesian Institute of Sciences (LIPI) for the use of its laboratory facilities.

References

[1] Veron, J.E.N. & Pichon, M., *Scleratinia of Eastern Australia Part IV, Family Poritidae,* Australian Institute of Marine Science Monograph series, **5**, p. 159, 1982.

[2] Veron, J.E.N., *Coral of Australia and the Indo-Pacific,* Angus and Robertson Publish, 1986.

[3] Veron, J.E.N., *Corals in Space and Time; The Biogeography and Evolution of the Scleractinaia,* Cornell, 1995.

[4] Veron, J.E.N., *Corals of the World,* Australian Institute of Marine Science, **3** (ed. M. Stafford-Smith), 2000.

[5] Forsman, Z., *Phylogeny and Phylogeography of Porites & Siderastrea (Scleractinia: Cnidaria) Species in The Caribbean and Eastern Pasific; Based on The Nuclear Ribosomal ITS Region,* A Dissertation, The Faculty of The Department of Biology and Biochemistry, University of Houston, pp. 153, 2003.

[6] Jokiel, P.S. & Coles, S.L., *Effects of Temperature on the Mortality and Growth of Hawaiian Reef Corals,* Mar. Biol., **43**, pp. 201-208, 1978.

[7] Highsmith, R.C., *Coral Growth Rates and Environmental Control of Density Banding,* J. Exp. Mar. Biol. Ecol., **37**, pp. 105-125, 1979.

[8] Crossland, C.J., *Seasonal Variations in the Rates of Calcification and Productivity in the Coral Acropora Formosa on A High Latitude Reef,* Marine Ecology Progress Series, **15**, pp. 135-140, 1984.
[9] Lough, J.M. & Barnes, D.J., *Environmental Controls on Growth of the Massive Coral Porites*, Journal of Experimental Marine Biology and Ecology, **245**, pp. 225-243, 2000.
[10] Goreau, T.F. & Goreau, N.I.*, The Physiology of Skeleton Formation in Corals. II. Calcium Deposition by Hermatypic Corals under Different Conditions in the Reef,* Biol. Bull. Mar. Biol. Lab. Woods Hole, **117**, pp. 239-250, 1959.
[11] Marubini, F., Barnett, H., Langdon, C. & Atkinson, M.J., *Dependence of Calcification on Light and Carbonate Ion Concentration for the Hermatypic Coral Porites compressa,* Marine Biology Progress Series, **220**, pp. 153-162, 2001.
[12] Scoffin, T.P., Tudhope, A.W., Brown, B.E., Chansang, H. & Cheeney, R.F., *Patterns and Possible Environmental Controls of Skeletogenesis of Porites lutea, South Thailand,* Coral Reefs, **11**, pp. 1-11, 1992.
[13] Fabricius, K.E., *Effects of Terestrial Run-off on the Ecology of Corals and Coral Reefs: Review and Synthesis,* Marine Polution Bulletin, **50**, pp. 125-146, 2005.
[14] Hughes, T.P., Baird, A.H. & Bellwood, D.R., *Climate Change, Human Impacts, and the Resilience of Coral Reefs,* Science, **301**, pp. 929-933, 2003.
[15] Gagan, M.K., Ayliffe, L.K., Beck, J.W., Cole, J.E., Druffel, E.R.M., Dunbar, R.B. & Schrag, D.P., *New Views of Tropical Paleoclimates from Corals*, Quartenary Sciences Reviews, **19**, pp. 45-64, 2000.
[16] De Villiers, S., Shen, G.T. & Nelson, B.K., *The Sr/Ca Temperature Relationship in Coralline Aragonite: Influence of Variability in (Sr/Ca) Seawater and Skeletal Growth Parameters*, Geochimica et Cosmochimica Acta, **58**, pp. 197-208, 1994.
[17] Cobb K.M., Charles, C.D., Cheng, H. & Edwards, R.L., *El Nino/Southern Oscillation and Tropical Pacific Climate during the Last Millennium*, Nature, **424**, pp. 271-276, 2003.
[18] Dodge, R.E. & Vaisnys, J.R., *Hermatypic Coral Growth Banding as Environmental Recorder*, Nature, **258**, pp. 706-708, 1975.
[19] Gagan, M.K., Chivas, A.R. & Isdale, P.J., *High-resolution Isotopic Records from Corals using Ocean Temperature and Mass Spawning Chronometers*, Earth and Planetary Science Letters, **121**, pp. 549-558, 1994.
[20] Gagan, M.K., Ayliffe, L.K., Hopley, D., Cali, J.A., Mortimer, G.E., Chappell, J., McCulloch, M.T. & Head, M.J., *Temperature and Surface-Ocean Water Balance of the Mid-Holocene Tropical Western Pacific*, Science, **279**, pp. 1014-101, 1998.

[21] Knutson, D.W., Buddemeier, R.W. & Smith, S.V., *Coral Chrono-meters: Seasonal Growth Bands in Reef Corals*, Science, **177**, pp. 270-272, 1972.

[22] Felis T. & Pätzold, J., *Climate Reconstruction from Annually Banded Corals*, Global Environmental Change in the Ocean and on Land, Eds., pp. 205-227, 2004.

[23] Carricart-Ganivet, J.P., Lough, J.M. & Barnes, D.J., *Growth and Luminescence Characteristics in Skeletons of Massive Porites from a Depth Gradient in The Central Great Barrier Reef*, Journal of Experimental Marine Biology and Ecology, **351**, pp. 27-36, 2007.

[24] De'ath, G., Lough, J.M. & Fabricius, K.E., *Declining Coral Calcification on the Great Barrier Reef*, Science, **323,** pp. 116-119, 2009.

[25] Cantin, N.E., Cohen, A.L., Karnauskas, K.B., Tarrant, A.M. & McCorkle, D.C., *Ocean Warming Slows Coral Growth in the Central Red Sea*, Science, **329**, pp. 322-325, 2010.

[26] Tanzil, J.T.I., Brown, B.E., Tudhope, A.W. & Dunne, R.P., *Decline in Skeletal Growth of the Coral Porites lutea from the Andaman sea, South Thailand between 1984-2005*, Coral Reef, 2009.

[27] Cooper, T.F., De'ath, G., Fabricius, K.E. & Lough, J.M., *Declining Coral Calcification in Massive Porites in Two Near Shore Regions of The Northern Great Barrier Reef*, Global Change Biology, **14**, pp. 529-538, 2007.

[28] Suharsono & Cahyarini, S.Y., *Reduced Trends of Annual Growth of Indonesian Porites over ~20 years*, Proceedings of the 12^{th} International Coral Reef Symposium, Cairns, Australia, 9-13 July, 2012.

[29] Purnamasari, I.A. & Cahyarini, S.Y., *Sea Surface Temperature and It's Correlation to Coral Linear Growth Rate of Seribu Island*, Geology and Mineral Resources Research, **20**(2), pp. 111-117, 2010.

[30] Helmle, K.P., Kohler, K.E. & Dodge, R.E., *Relative Optical Densitometry and the Coral X-Radiograph Densitometry System: Coral XDS*, Presented Poster, Int. Soc. Reef Studies 2002, European Meeting, Cambridge, England, Sept. 4-7, 2002.

[31] Welly, M., Darma, N. & Basuki R., *Profile Marine Protected Area of Nusa Penida Klungkung, Bali Province*, The Nature Conservacy – Indonesia Marine Program (TNC-IMP), 2010.

[32] Helmle, K., *Relative Optical Densitometry and the Coral X-radiograph Densitometry System: Coral XDS*, Nova Southeastern University Oceanographic Center, National Coral Reef Institute, http://www.nova.edu/ocean/coralxds/, (4 January 2013).

[33] Buddemeier, R.W., Maragos, J.E. & Knutson, D.W., *Radiographic Studies of Reef Coral Exoskeleton: Rates and Patterns of Coral Growth*, Journal of Experimental Marine Biology and Ecology, **14**, pp. 179-200, 1974.

[34] Dodge, R.E & Thomson, J., *The Natural Radiochemical and Growth Records in Contemporary Hermatypic Corals from the Atlantic and Carribean*, Earth Planet. Sci. Lett., **23**, pp. 313-322, 1974.

[35] Macintyre, I.G. & Smith, S.V., *X-radiographic Studies of Skeletal Development in Coral Colonies,* Proc. 2nd Int. Coral Reef Symp., Brisbane, **2**, pp. 277-278, 1974.

[36] Moore, W.S. & Krishnaswarni, S.*, Correlation of X-radiography Revealed Banding in Corals with Radiometric Growth Rates,* Proc. 2nd Int. Coral Reef Symp., Brisbane, **2**, pp. 269-276, 1974.

[37] Tanzil, J.T.I, *Environmental Controls of Coral Growth: Data Driven Multi-Scale Analyses of Rates and Patterns of Groth in Massive Porites Corals around the Thai-Malay Peninsula*, pp. 46-69, 2013.

[38] Charles, C.D., Cobb, K., Moore, M.D. & Fairbanks, R.G., *Monsoon-tropical Ocean Interaction in A Network of Coral Records Spanning The 20th Century,* Marine Geology*,* **201**, pp. 207-222, 2003.