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Hard Coral (*Porites Lutea*) Growth Simulation using Fuzzy Logic Method in Tunda Waters, Banten Province

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Abstract

Corals grow annually at varying rates, influenced by environmental conditions. As key indicators of marine ecosystem health, studying coral growth is essential for predicting the impacts of environmental change. While previous research has explored coral growth extensively, most studies focus on existing conditions and the descriptive influence of environmental parameters. In fact, coral growth time-series data offer potential for deeper analysis, particularly in identifying dominant periodicities and enabling long-term projections. This study aims to develop an annual coral growth model using fuzzy logic approach. The Indian Ocean Dipole (IOD) is identified as a significant factor influencing the growth of Porites lutea in Tunda Island. Variations in sea surface temperature during IOD events notably affect coral growth, with positive IOD phases (IOD+) generally enhancing it. Analysis shows that the annual growth rings of Porites lutea in the northern station of Tunda Island, which borders open waters respond more slowly to SST fluctuations compared to the southern station, which is more sheltered. Fuzzy simulation results suggest that corals may be able to adapt to climate change. By the year 2085, coral growth is projected to recover from -0.75 cm to 0.1 cm by 2100. Based on SST projections from 1900 to 2100, SST anomalies are expected to continue increasing, reaching +0.45 °C.

Keywords: Corals Growth, Fuzzy Logic, Indian Ocean Dipole, Sea Surface Temperature, Tunda Island

1. Introduction

A defining feature of tropical waters is their shallow coastal zones, which are dominated by coral reef ecosystems (Graham *et al* 2017). Coral reefs are ancient and majestic ecosystems with high productivity and remarkable biodiversity. However, they are also fragile, highly sensitive, and prone to stress from environmental changes (Goreau and Hayes, 2008). The health of coral reefs in the coastal waters of developing island nations, such as Indonesia, has been increasingly threatened, one of the major disturbances being coral bleaching (Westmacott et al., 2000; Virgen-Urcelay and Donner, 2023). Coral bleaching is triggered by several stressors, including abnormal sea surface temperatures, high ultraviolet radiation, insufficient light, elevated turbidity and sedimentation, disease, abnormal salinity levels, and pollution (Alvarez *et al* 2023; Grottoli *et al*., 2025).

Global warming has become a widely discussed issue, particularly regarding its impacts on coral reef ecosystems (Mladenov, 2020). An increase in air temperature is often followed by a rise in sea surface temperature (SST). This warming is thought to contribute to sea-level rise due to polar ice melt, alter ocean current patterns, change atmospheric pressure, and ultimately shift weather and climate patterns globally. Key factors influencing coral growth during climate change include rising sea levels, increasing sea surface temperatures, changes in carbonate chemistry, heightened ultraviolet radiation, and the potential for more frequent storms (Hoegh-Guldberg *et al* 2017; Perry *et al*., 2015; Zhu *et al*., 2022).

This study builds on previous research by Ampou et al. (2017) and Lalang et al., 2014, which examined the growth dynamics of *Porites lutea* corals using stable isotope analysis at two sites with contrasting oceanographic conditions: the windward and leeward sides. The term *windward* refers to the side of an island or reef facing the prevailing wind, typically experiencing higher exposure to wave energy and ocean currents. In contrast, the *leeward* side is sheltered from direct winds, resulting in calmer waters (Lenihan *et al* 2015). Such differences in hydrodynamic conditions can influence SST, which in turn plays an important role in modulating coral growth. Through this approach, the present study aims to identify long-term growth trends and quantitatively evaluate the relationship between coral growth rates and SST at windward and leeward sites.

Massive corals such as *Porites lutea* form annual growth bands that record environmental changes over time (Tito *et al* 2016; Zamani et al., 2016). While many previous studies have focused on present-day conditions and the relationship between environmental parameters and coral growth, long-term time series data also hold great potential for periodicity analysis and future projections. It is therefore important not only to assess current conditions but also to simulate coral growth under different future climate scenarios. One of the key factors known to influence SST in western Indonesia, including Tunda Island, is the Indian Ocean Dipole (IOD)—a regional climate anomaly characterized by differences in SST between the western and eastern Indian Ocean. During a positive IOD phase (IOD+), the western Indian Ocean becomes warmer, while the eastern part cools (Saji et al., 1999). This SST gradient can influence the growth rates of *Porites lutea*. The main objective of this research is to predict climate change impacts on SST and the growth rates of *Porites lutea* over time, projecting their dynamics through the year 2100.

2. Research Methods

2.1. Study Period and Location

This research was conducted from May 2016 to July 2017. Coral growth data were obtained from the study by Lalang et al., 2014, collected in October 2014 at two observation stations: the northern (windward) and southern (leeward) sites (**Figure 1**). Analysis and identification of sea surface temperature and coral growth were carried out at the Oceanography Laboratory, Faculty of Fisheries and Marine Sciences, IPB University.

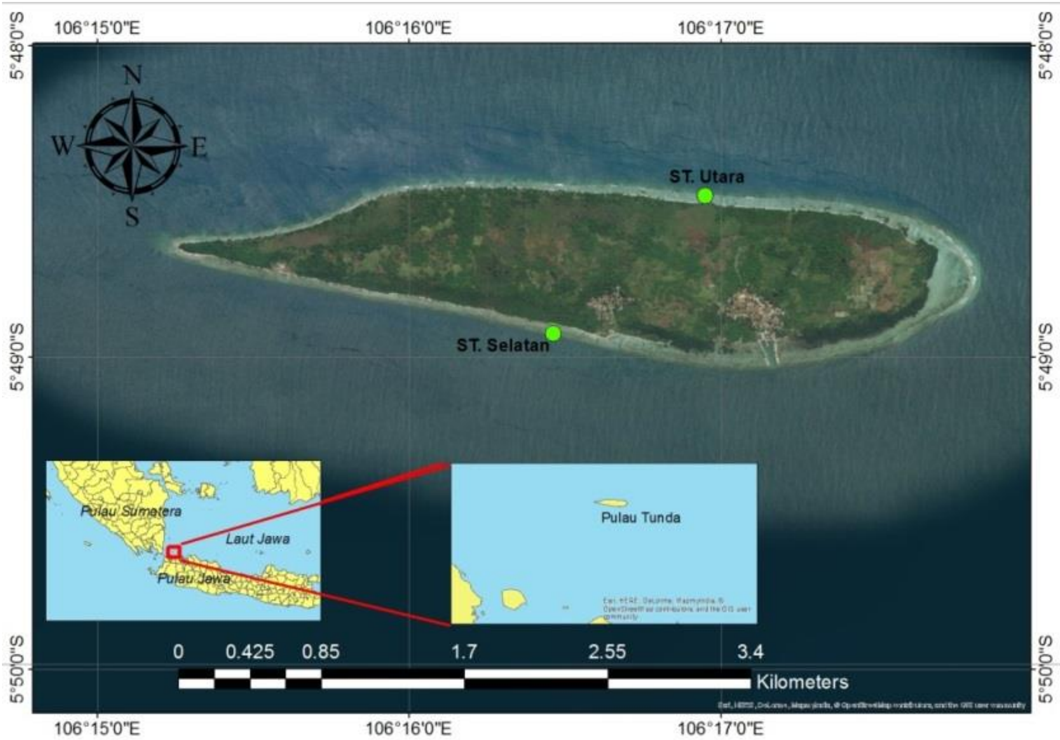


Figure 1. *Research Location on the Northern Side (Windward) and the Southern Side (Leeward) of Tunda Island.*

2.2. Data Sources

This study utilized coral growth data obtained from the previous work of Lalang et al., 2014, which specifically analyzed the annual growth of massive *Porites lutea* colonies using X-ray imaging techniques (**Figure 2a**). This method enabled the determination of coral growth rates by identifying annual skeletal banding, as well as assessing the direction and rate of skeletal extension (Riska et al., 2015). At the northern station (windward), a continuous growth time series was available from 1950 to 2015, providing a 66-year dataset. In contrast, data from the southern station (leeward) covered a shorter period, from 1968 to 2015. This difference in record length was due to the size of representative coral colonies available at each site (Riska et al., 2015). These datasets formed the primary basis for analyzing long-term coral growth trends and for developing simulation models to project growth patterns through the end of the 21st century.

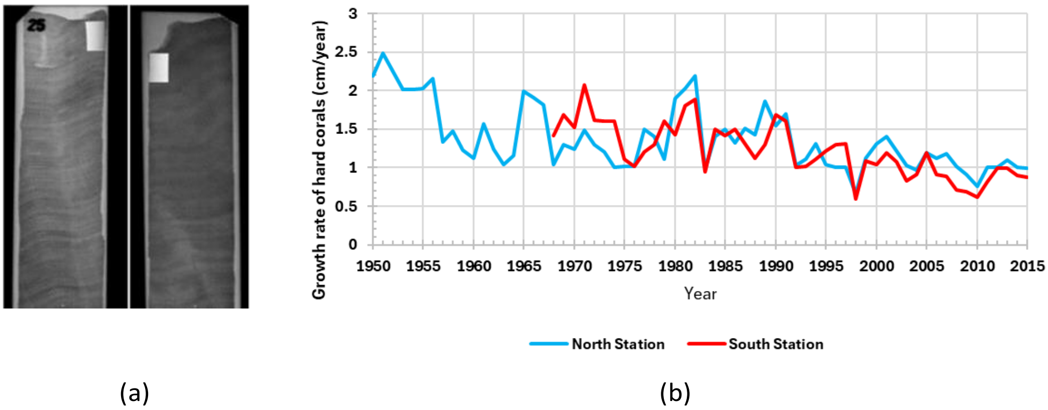


Figure 2a X-ray Results for Determining the Annual Growth Line of Hard Corals (Riska et al., 2015); b. Coral Growth Rate (Lalang et al., 2014).

Sea surface temperature (SST) data used in this study were obtained from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, 2008), which provides globally scaled oceanographic datasets. The SST dataset utilized comprised monthly records covering the Indian Ocean region, with an observation period spanning from January 1950 to February 2015. The SST values analyzed in this study represent averaged temperatures from two equatorial sectors of the Indian Ocean: the western sector (50° E – 70° E and 10° S – 10° N) and the eastern sector (90° E – 110° E and 10° S – 0° N). The temperature difference between these two regions served as the basis for calculating the Indian Ocean Dipole (IOD) index, which was subsequently used to evaluate the influence of climate variability on coral growth.

2.3. Research Procedures

2.3.1. Indian Ocean Dipole Analysis

The monthly SST data obtained were first averaged to determine the annual mean SST anomalies. These SST anomalies were then smoothed using a moving average method to derive the annual SST anomaly values. Once the annual SST anomalies for the western and eastern equatorial Indian Ocean were determined, the Dipole Mode Index (DMI) was calculated following the approach of Cai *et al*. (2019).

The DMI represents the intensity of the IOD and is expressed as the SST anomaly difference between the western equatorial Indian Ocean (50° E – 70° E and 10° S – 10° N) and the eastern equatorial Indian Ocean (90° E – 110° E and 10° S – 0° N). A positive DMI value indicates a positive IOD phase, whereas a negative value indicates a negative IOD phase (JAMSTEC, 2008).

2.3.2. Wavelet Analysis

Wavelet analysis is a signal processing method that interprets time-series data as a signal and transforms the one-dimensional time series into a two-dimensional representation. The method has been widely applied across various scientific fields—for example, Torrence and Compo (1998) and Gu and Philander (1995) used it to analyze the El Niño–Southern Oscillation; Meyers et al. (1993) applied it to study ocean wave dispersion; and Koontanakulvong (2008) used it to examine temperature changes resulting from climate variability. Wavelet transformation is particularly well-suited for detecting transient periodic fluctuations and parameter changes, as it can focus on specific time intervals within a dataset (Hidayat, 2002).

2.3.3. Analisis Logika Fuzzy

Fuzzy logic is a method used to map an input space into an output space (Kusumadewi & Purnomo, 2004). In 1965, Lotfi Zadeh, a professor at the University of California, Berkeley, modified set theory by introducing the concept that each member of a set could have a degree of membership with a continuous value ranging from 0 to 1. This concept is referred to as a fuzzy set (Kusumadewi, 2002). The fuzzy method is a system built upon rule-based knowledge, typically expressed as a collection of IFS–THEN rules.

The reasons for using fuzzy logic include: its concepts are easy to understand; it is highly flexible; it tolerates imprecise data; it can model highly complex nonlinear data; it allows expert experience to be incorporated directly without the need for training processes; and it can work in conjunction with conventional control techniques using natural language (Pratiwi and Prayitno, 2005). Fuzzy logic is implemented in three stages (**Figure 3**).

1. Fuzzification – mapping crisp inputs into fuzzy sets.
2. Inference – generating fuzzy rules.
3. Defuzzification – transforming fuzzy outputs into crisp values.

Figure 3. Fuzzy Logic Stages

The fuzzification stage is the process of converting system inputs with crisp values into linguistic variables using membership functions stored in the fuzzy knowledge base (Sutojo et al., 2011). A fuzzy subset is a distinct subset of the input and output variables. Fuzzy rules link input and output variables through these subsets, typically expressed in the form of IF…THEN statements. For example: IF (X IS A) AND (Y IS B) THEN (Z IS C), where A, B, and C are fuzzy sets. Given a set of fuzzy rules, the system can respond quickly and efficiently.

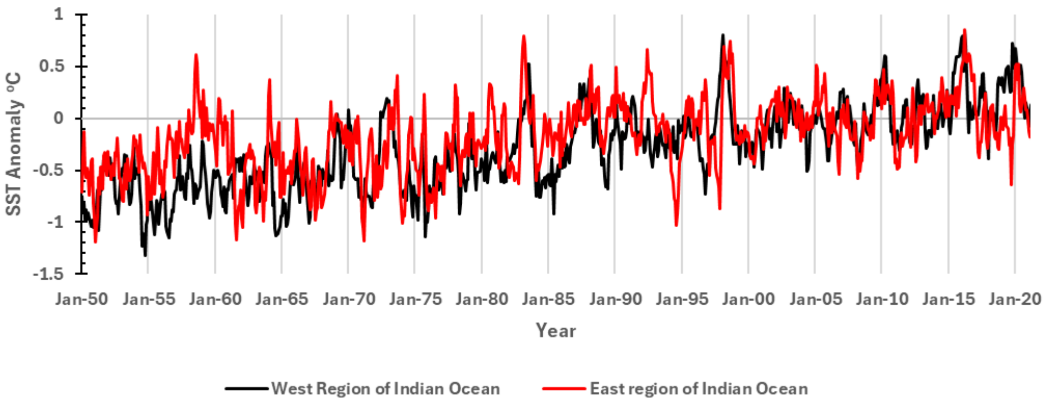
According to Yager and Kacprzyk (2018), several methods exist in fuzzy logic, including the Mamdani and Tsukamoto approaches. This study employed the Mamdani method, in which the MIN function is used for implication and the MAX function is applied for rule composition to generate a new fuzzy set. Furthermore, the defuzzification process in the Mamdani method was carried out using the Centroid method, with the following equation.

3. Results and Discussion

3.1. Sea Surface Temperature

The analysis of sea surface temperature (SST) in the western and eastern equatorial Indian Ocean revealed a fluctuating pattern of annual variability (**Figure 4**). Overall, SST in both regions showed an increasing trend from 1950 to 2015. Significant warming in the western region was recorded in years such as 1966–1967, 1969–1970, 1973–1974, 1983–1984, 1986–1987, 1997–1998, 2009–2010, and 2015–2016, compared to the eastern region. The maximum SST anomaly occurred in 1997, with a deviation of 1.29 °C.

This sharp temperature rise was triggered by a positive Indian Ocean Dipole (IOD+), during which the waters of the western Indian Ocean warmed significantly while the eastern sector—including Indonesian waters—experienced cooling (Vinayachandran et al., 2002). During a positive IOD phase, Indonesian waters tend to be cooler than normal conditions (Dewi et al., 2020). Furthermore, the SST increase in the western region was amplified by the simultaneous occurrence of the El Niño phenomenon in that year (Zhang et al., 2022). This aligns with the findings of Heryati et al. (2018), who reported that during El Niño events, SST in Indonesian waters is generally lower than under normal conditions. The combination of a positive IOD and El Niño in 1997 was therefore the main driver of the maximum SST anomaly.



Inset

Figure 4. SST Anomalies in the Western and Eastern Equatorial Indian Ocean.

The El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are two major climate systems influencing weather variability and sea temperature in Indonesian waters. Although they are spatially distinct, ENSO being centered in the Pacific Ocean and the IOD occurring in the Indian Ocean share a complex relationship (Amri et al., 2013; Krisnanto et al., 2024). ENSO can affect the onset and intensity of the IOD, particularly when a strong El Niño phase has the potential to amplify a positive IOD. However, the IOD can also arise independently, without ENSO involvement, as a response to local variability in the Indian Ocean. Thus, while ENSO may act as an external factor that strengthens the IOD, the occurrence of the IOD is not necessarily dependent on ENSO. Their relationship is non-stationary and depends on prevailing global atmospheric and oceanic conditions at any given time (Polonsky and Torbinsky, 2021).

In contrast to other years, 1958 recorded a negative sea surface temperature (SST) anomaly between the western and eastern Indian Ocean, with a maximum difference of 1.26 °C. This indicates that the eastern Indian Ocean experienced greater warming than the western side—a hallmark of a negative Indian Ocean Dipole (IOD) event. This finding is consistent with observations in 1958, when a strong negative IOD resulted in cooler SST in the western Indian Ocean and warmer SST in the eastern Indian Ocean, including Indonesian waters (Rao et al., 2002). Such events are generally associated with increased rainfall over the Indonesian maritime continent.

A positive IOD structure is characterized by warmer-than-normal SST anomalies in the western Indian Ocean and cooler-than-normal SST anomalies in the eastern Indian Ocean. During such events, rainfall increases over the eastern tropical African region, while drought conditions tend to occur across the Indonesian archipelago (Ashok et al., 2001; Nur'utami and Hidayat, 2016). Conversely, during a negative IOD event, SST in the eastern Indian Ocean becomes warmer, while the western region experiences cooling. As a result, the center of convection and rainfall shifts toward Indonesia and surrounding areas, potentially increasing rainfall intensity (Vinayachandran et al., 2001).

The SST anomalies in the two regions were then differenced to determine the Dipole Mode Index (DMI) intensity. The DMI is calculated based on the difference between the average SST in the western and eastern equatorial Indian Ocean. An increase in SST during a given year may indicate the occurrence of a positive IOD event (Saji et al., 1999). **Figure 5** presents DMI index values for the period 1950–2021. Based on DMI fluctuations, the type of IOD event associated with globally significant SST changes can be identified. In **Figure 5**, positive IOD events are represented by red bars, while negative IOD events are shown in blue. **Table 1** lists the years in which strong positive and negative IOD events occurred.

Table 1. Years of IOD Occurrence Based on the DMI Index.

IOD Positif	*IOD Negatif*
1961, 1972, 1976, 1982, 1994, 1997, 2007, 2012	1954, 1955, 1958, 1964, 1975, 1980, 1983, 1989, 1992, 1996,1998

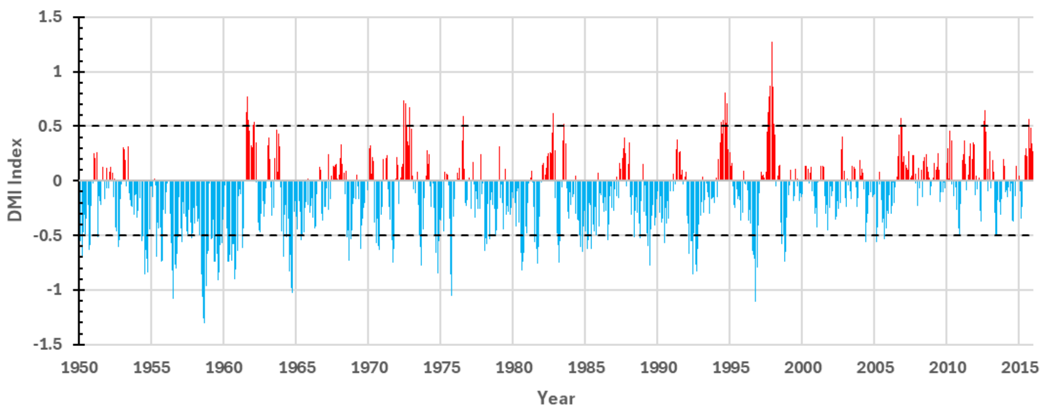


Figure 5. IOD Phenomenon in the Indian Ocean from 1950 to 2021.

3.2. Relationship Between Coral Growth and the DMI Index

The relationship between coral growth and the Dipole Mode Index (DMI), as shown in **Figure 6**, indicates that the coral growth pattern at the Northern Station of Tunda Island is influenced by the Indian Ocean Dipole (IOD) phenomenon, in both positive and negative phases, occurring in certain years in the western waters of Indonesia. The IOD phenomenon indirectly affects the dynamics of Sea Surface Temperature (SST) in the study area, which in turn influences the physiological condition and growth of corals, particularly *Porites lutea.*

Statistical analysis shows that positive IOD events have no significant effect on coral growth rates, with a very low correlation value of +0.1. This suggests that although SST increases during the positive IOD phase, such events do not necessarily result in direct increases in coral growth. In fact, extreme temperature increases during strong positive IOD phases—such as in 1997—were correlated with sharp declines in coral growth, presumably due to excessive thermal stress. Conversely, negative IOD events show a more significant relationship, with a correlation value of -0.3, indicating that the stronger the intensity of the negative IOD, the more likely coral growth rates in the northern part of Tunda Island decline. This negative correlation suggests that although the negative IOD phase is generally associated with warmer and more humid conditions in Indonesian waters, temperature increases beyond the physiological tolerance threshold of corals can negatively affect their growth. In other words, SST fluctuations occurring during both positive and negative IOD phases cannot be linearly linked to coral growth rates at this location. These findings align with several previous studies, which state that the relationship between sea temperature changes and coral growth rates does not always follow a linear pattern (Rani et al., 2004; Nugraha, 2008; Tito et al., 2013).

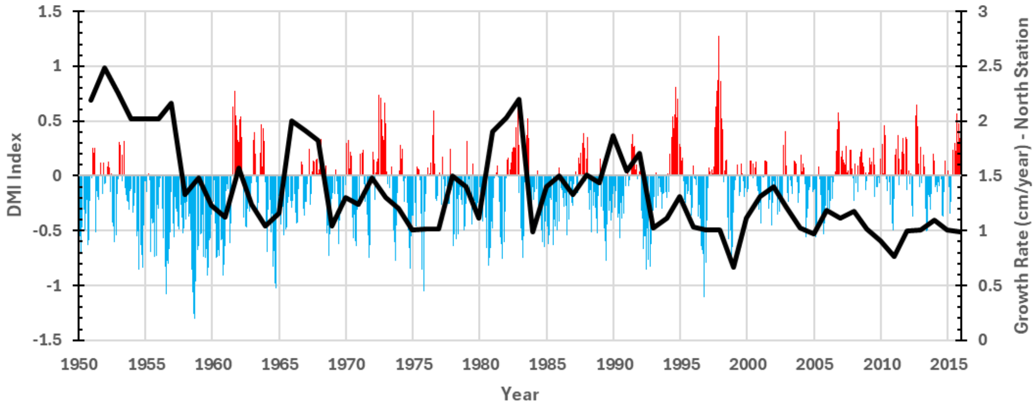


Figure 6. SST Anomalies and Coral Growth (Northern Station).

A different pattern was observed in the growth rate of *Porites lutea* corals at the southern station of Tunda Island, as presented in **Figure 7**. It appears that positive IOD events had a stronger influence on increasing coral growth rates on the southern side, with a correlation coefficient of 0.6. This finding indicates that the more intense the positive IOD phenomenon, the greater the increase in coral growth rates on the southern side of Tunda Island. However, extreme positive IOD phases, which are associated with a significant drop in sea surface temperature (SST) in the eastern equatorial Indian Ocean, including Indonesian waters, can also disrupt coral growth in this region.

The correlation between the negative IOD index and SST on the southern side of Tunda Island shows a value of -0.3, meaning that higher negative IOD intensity tends to reduce the growth rate of *Porites lutea* corals at the southern station. Nevertheless, it is important to note that during very strong positive IOD phases, such as in 1997, the SST decline in Indonesian waters could reach extreme levels. Such conditions have the potential to disrupt coral metabolic processes and slow their growth.

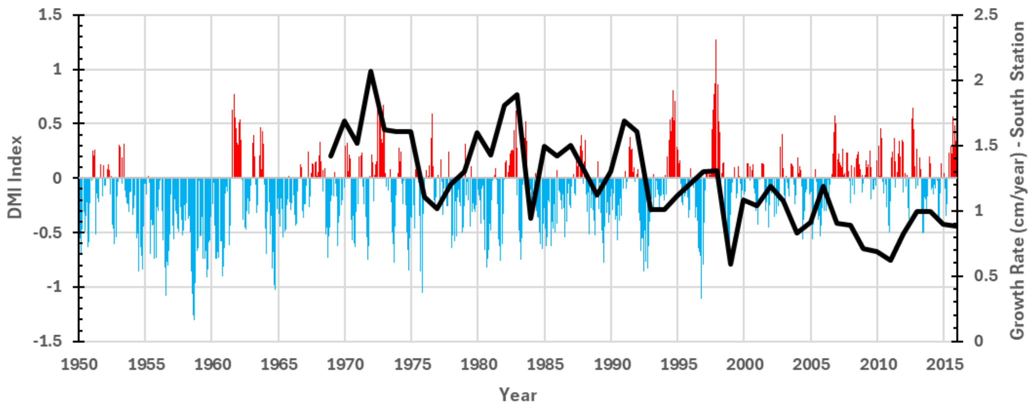


Figure 7. SST Anomalies with Hard Coral Growth (South Station).

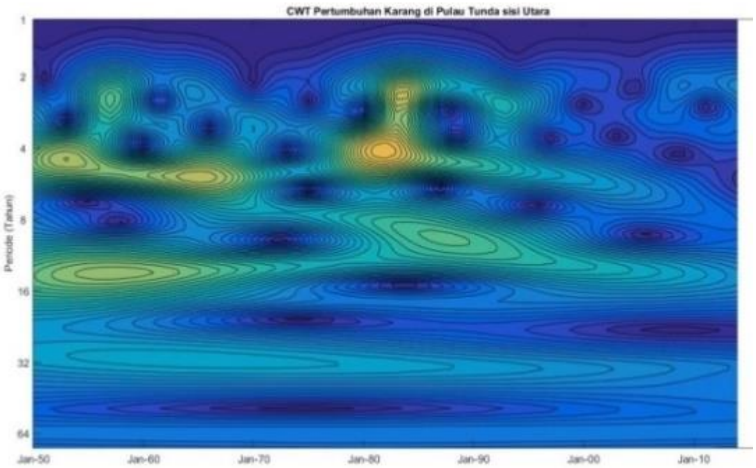
Although the overall trend of positive IOD events appears to be beneficial for coral growth on the southern side, the biological response of corals remains highly dependent on the intensity and duration of the accompanying temperature anomalies. Meanwhile, the correlation between negative IOD and coral growth at the southern station, with a value of -0.3, indicates a negative but relatively weak relationship. This suggests that the greater the intensity of negative IOD, the greater the tendency for *Porites lutea* growth rates in the area to decline.

In addition to global oceanographic factors such as the IOD, geographical location also plays a crucial role in influencing coral growth rates around Tunda Island. The northern station, which is directly exposed to open waters, exhibits a slower response to changes in sea surface temperature (SST), with a lag time of approximately 3 to 7 years. This indicates that changes in SST take longer to affect coral growth rates in this area. This slower response is likely related to the high dynamics of ocean currents, wave exposure, and the influence of regional oceanographic systems, which cause environmental fluctuations to occur more gradually yet remain relatively stable.

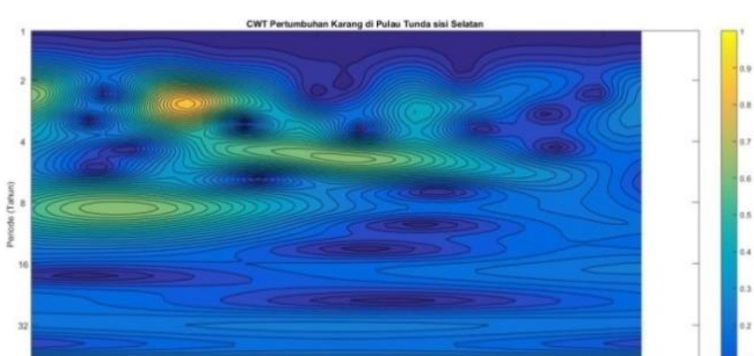
In contrast, the southern station—situated in waters more sheltered from the direct influence of the open ocean—shows a much faster response to SST variations, with a reaction time of only about ±1 year. The relatively calm and enclosed characteristics of the southern waters allow changes in temperature, nutrient availability, and water clarity to more rapidly affect the physiological condition of corals. This explains why IOD events tend to have a more significant impact on coral growth on the southern side compared to the northern side.

3.3. Coral Growth Periodicity

The periodicity of coral growth was further analyzed using Wavelet analysis. This method determines the degree of coherence between the periodic cycles of coral growth and the study period spanning 1950–2015.



(a)



(b)

Figure 8. Wavelet Analysis Results for the Northern Station (a) and Southern Station (b) of Tunda Island during 1950-2014.

The results for coral growth at the northern station (ST. Utara) during 1950–2015 (**Figure 8a**) indicate a dominant 4-year (interannual) growth cycle, with maximum coherence values reaching 0.9 for almost the entire study period. In addition, coral growth also exhibited cycles of 3, 5, 6, 10, and 14 years, with coherence levels reaching 0.6. Longer cycles of 32 and 64 years were also detected, although with lower coherence values of less than 0.4.

At the southern station (ST. Selatan) during 1968–2015 (**Figure 8b**), a similar pattern was observed, with dominant growth cycles of 3–4 years and 64 years, the former showing coherence values close to 1. Additional cycles of 5 and 8 years were also identified, with coherence levels reaching 0.6. A 32-year cycle was present but with an intensity of less than 0.5.

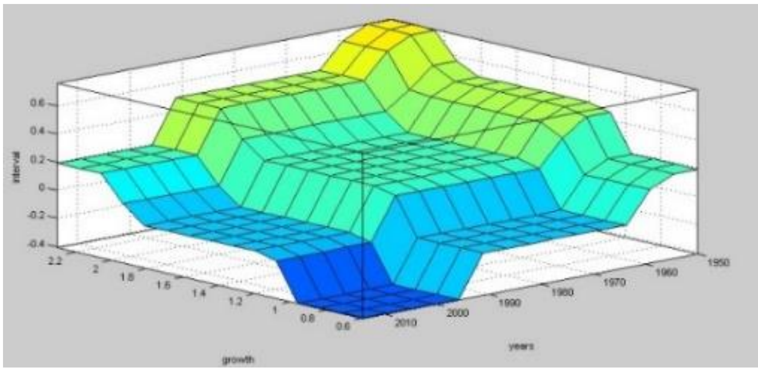
Overall, the northern station was dominated by a 4-year growth cycle, while the southern station was dominated by a 3-year cycle. These results indicate that coral growth periodicity in both stations is predominantly driven by interannual cycles (3–5 years).

3.4. Coral Growth Simulation

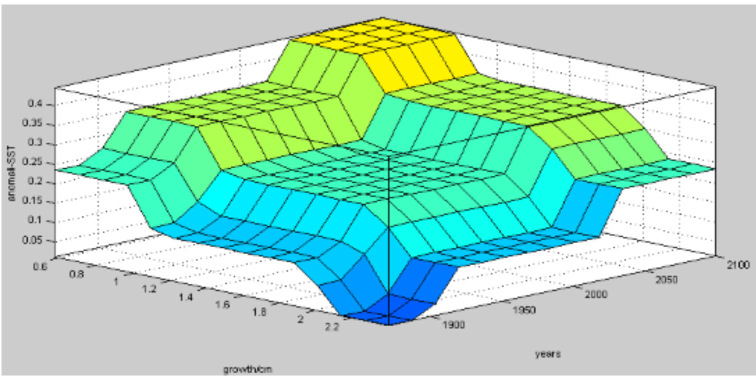
he coral growth simulation using the Mamdani fuzzy logic method produced a pattern that tends to decline in both growth size and its anomalies. **Figure 9a** presents the results of the fuzzy logic interpretation based on the defined classes and rules. The figure shows that corals in the past had relatively large sizes, indicated by the yellow colour.

During the homeostatic phase (1964–1994), coral conditions were relatively stable, with an average size of around ±0.2 cm. However, from 1994 to 2014, coral size underwent continuous degradation. Growth decreased to a range of 0.6 cm to 0.9 cm, with anomalies reaching −0.4 cm (meaning the size decreased by 0.4 cm/year) between 1995 and 2014.

Figure 9b illustrates that SST changes are projected to increase, reaching up to 0.45°C by the year 2100.



(a)



(b)

Figure 9a. Coral Growth Based on Fuzzy Logic Method Interpretation; b Simulation of SST Changes from 1900-2100.

The interpretation of the fuzzy logic output was followed by an adjustment of the universal set. Based on existing conditions, the universal set initially ranged from 1950 to 2014. It was then modified in accordance with the research objective, which was to simulate coral reef growth from the year 1900 to 2100.

The coral reef growth simulation, as shown in **Figure 10**, indicates that coral reefs do not experience extinction; instead, they grow from a minimum value of −0.75 cm to 0.1 cm. Therefore, it can be concluded that coral reefs are capable of adapting despite experiencing environmental change pressures in their surroundings.

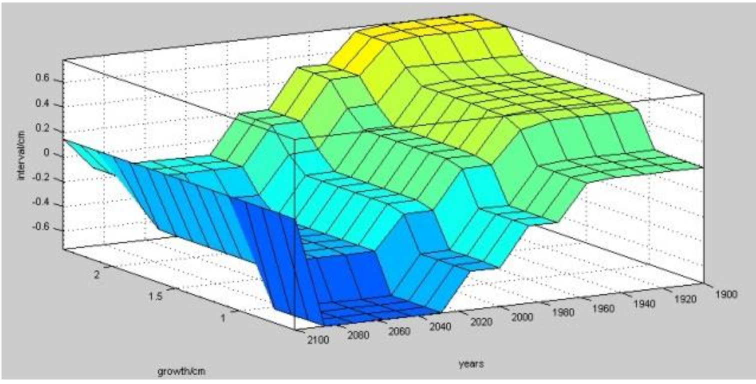
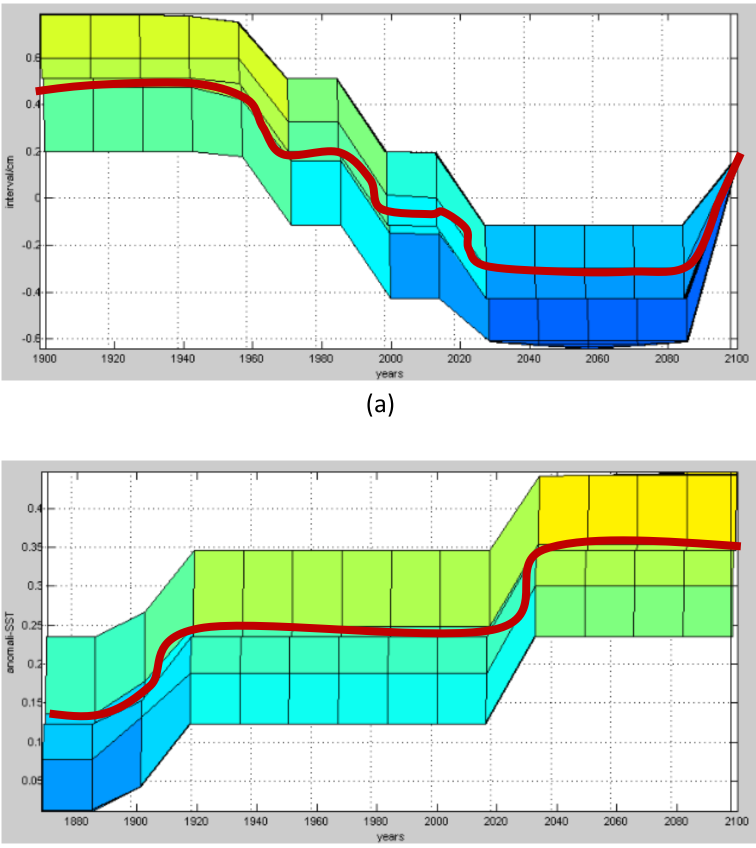


Figure 10. Front View of Coral Growth Simulation from 1950-2100.



(a)

(b)

Figure 11 Simulation of Coral Growth Rate (a) and Simulation of SST Changes (b).

If the perspective of Figure 10 is changed to a side view, the result is shown in Figure 11a. The assumptions used in the settings can be well interpreted, indicating that in the past, corals were relatively large in size, with growth anomalies ranging from 0.2 to 0.8 cm. Over time, the size of corals in Tunda Island has gradually decreased. By the year 2085, however, corals are projected to adapt and increase in size, with anomalies exceeding 0.1 cm by 2100.

When a growth curve or projection is created for the period 1900–2100, it can be seen that the coral growth rate steadily declines over the years (**Figure 11a**). Meanwhile, the SST projection shows a continuous increase from 1900 to 2100 by 0.2 °C (**Figure 11b**). This study predicts that coral growth rates in Tunda Island have a negative correlation with changes in SST.

4. Conclusions

The conclusions section should come in this section at the end of the article, before the This study demonstrates that the growth rate of *Porites lutea* corals in Tunda Island is influenced by sea surface temperature (SST), the Indian Ocean Dipole (IOD) phenomenon, and geographical location. Observation at the northern station, which borders open waters, shows that coral growth responds more slowly to changes in SST (3–7 years) and has a weak correlation with IOD. In contrast, observations at the more sheltered southern station indicate a much faster response (±1 year), with positive IOD showing a fairly significant correlation with increased coral growth (r = 0.6).

The analysis results indicate that corals will not become extinct but will instead grow, reaching 0.1 cm in 2085 from a minimum growth anomaly of –0.75 cm. Coral growth simulations under SST changes show that SST will increase by up to 0.45 °C. The SST curve or projection indicates a rise of 0.2 °C by the year 2100. This study predicts that coral growth rates in Tunda Island have a negative correlation with SST changes, where an increase in SST will be followed by a decrease in coral growth rate.

For future research, it is recommended to include additional parameters such as demographics, industrial activities, rainfall, and other factors that influence coral reef growth.

Conflicts of Interest

The authors declare that there are no conflicts of interest

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