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The Influence of the Indian Ocean Dipole (IOD) Phenomenon on Sea Surface Temperature and Chlorophyll-a in the Sunda Strait

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ABSTRACT

The Indian Ocean Dipole (IOD) interannual ocean-atmosphere anomaly phenomenon impacts marine ecology in the Sunda Strait region. This study aims to analyze the influence of IOD on sea surface temperature (SST) and chlorophyll-a (Chl-a) in the Sunda Strait. Monthly time series data from 2006-2020 (15 years) were obtained from Copernicus Marine Service, and analyzed using Pearson Correlation, Cross Wavelet Transform (XWT), and Wavelet Coherence Transform (WTC) methods. The results showed that for 15 years (2006-2020) the ranged from 27.63°C-30.55°C and Chl-a ranged from 0.082 mg.L^{-1}- 3.611 mg.L^{-1}. In the Western Season (JJA) and Transitional I (MAM), SST tends to be warm and Chl-a is low, while in the Eastern Season (DJF) and Transitional II (SON) SST tends to be cold and Chl-a is high. During IOD+, SST relatively low and Chl-a is high, while during IOD-, SST tends to be high and Chl-a is low.While Pearson correlation shows weak global linear relationships for SST-IOD (r = -0.2627) and Chl-a-IOD (r = 0.3794), XWT and WTC analyses reveal significant localized coherence in the time–frequency domain. These results are complementary rather than contradictory; wavelet-based methods capture transient, non-stationary interactions during specific periods and scales that global linear correlations fail to detect. The results of XWT and WTC analysis show a strong relationship between SST and Chl-a to the IOD.

Keywords: Indian Ocean Dipole (IOD), Sea Surface Temperature (SST), Chlorophyll-a (Chl-a), Wavelet Transform, Marine Ecology

ABSTRAK

Fenomena anomali intertahunan laut-atmosfer *Indian Ocean Dipole* (IOD) berdampak pada ekologi laut di wilayah Selat Sunda. Penelitian ini bertujuan untuk menganalisis pengaruh IOD terhadap suhu permukaan laut (SPL) dan klorofil-a (Chl-a) di Selat Sunda. Data deret waktu bulanan dari tahun 2006-2020 (15 tahun) diperoleh dari *Marine Copernicus*, dan dianalisis menggunakan metode Korelasi Pearson, *Cross Wavelet Transform* (XWT), serta *Wavelet Coherence Transform* (WTC). Hasil penelitian menunjukkan bahwa selama 15 tahun (2006-2020), rentang SPL berkisar antara 27,63°C–30,55°C dan Chl-a berkisar antara 0,082 mg.L^{-1} –3,611 mg.L^{-1}. Pada Musim Barat (JJA) dan Transisi I (MAM), SPL cenderung hangat dan Chl-a rendah, sedangkan pada Musim Timur (DJF) dan Transisi II (SON), SPL cenderung dingin dan Chl-a tinggi. Selama fase IOD+, SPL relatif rendah dan Chl-a tinggi, sebaliknya selama fase IOD-, SPL cenderung tinggi dan Chl-a rendah. Meskipun korelasi Pearson menunjukkan hubungan linier global yang lemah untuk SPL-IOD (r = -0,2627) dan Chl-a-IOD (r = 0,3794), analisis XWT dan WTC mengungkapkan koherensi lokal yang signifikan dalam domain waktu-frekuensi. Hasil ini bersifat saling melengkapi dan bukan kontradiktif; metode berbasis *wavelet* mampu menangkap interaksi transien dan non-stasioner selama periode dan skala tertentu yang gagal dideteksi oleh korelasi linier global. Hasil analisis XWT dan WTC menunjukkan adanya hubungan yang kuat antara SPL dan Chl-a terhadap IOD.

Kata kunci: *Indian Ocean Dipole* (IOD), Suhu Permukaan Laut (SPL), Klorofil-a (Chl-a), *Wavelet Transform*, Ekologi Laut

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1. Introduction

The Sunda Strait is a pivotal maritime passage for Indonesian water mass circulation, separating Sumatra and Java while connecting the Java Sea with the Indian Ocean. Driven by sea-level differentials, a consistent flow from the Java Sea to the Indian Ocean facilitates vital water mass exchange between these two basins (Amri, 2008; Li et al., 2018). This mixing significantly enhances local water quality, particularly influencing SST and Chl-a concentrations (Tarigan et al., 2020). These processes are further modulated by IOD-related variability; for instance, positive IOD phases often intensify upwelling and vertical mixing, leading to more pronounced fluctuations in thermal regimes and nutrient enrichment.

Geographically, the strait features a steep bathymetric gradient (tubir) where shallow coastal waters meet the deep ocean. This north-south extending boundary serves as a primary site for upwelling, particularly during the Southeast Monsoon and Transition Season II (Amri, 2008). Upwelling transports cold, nutrient-rich deep water to the euphotic zone, fueling phytoplankton growth and creating highly productive fishing grounds (Wirasatriya et al., 2018). Within the Sunda Strait, the dynamics of this localized productivity are intrinsically linked to broader atmospheric-oceanic interactions, primarily governed by the Indian Ocean Dipole (IOD).

As a dominant climate mode in the Indian Ocean, the IOD influences the Sunda Strait by altering upwelling intensity through shifts in wind stress and SST gradients (Xu et al., 2018). During a positive IOD phase, the eastern Indian Ocean experiences anomalous cooling and enhanced upwelling, whereas warmer waters shift toward the western basin (Alamsyah et al., 2024). Conversely, negative IOD events are characterized by anomalously warm SSTs and a deeper thermocline in the eastern basin, which restricts nutrient transport to the surface and consequently reduces Chl-a levels (Oktaviani et al., 2021). Such IOD-triggered variability plays a crucial role in modulating regional ecological dynamics, underscoring the profound link between physical oceanographic processes and biological productivity (Fahlevi et al., 2022).

Despite its strategic importance, comprehensive long-term studies on the Sunda Strait remain scarce. While Amri et al. (2007) investigated seasonal oceanographic conditions, their study spanned only four years and did not account for IOD influences. Similarly, in-situ observations by Amri et al. (2014) were limited to a single season in 2010. Most existing research has focused on adjacent regions, such as the Bali Strait (Hafizhurrahman et al., 2015), Karimata Strait (Asyam et al., 2024), and Western Sumatra (Susilo et al., 2022). While Kunarso et al. (2012) and Yuniarti et al. (2013) successfully linked IOD variability to changes south of Java and Bali, the Sunda Strait remains under-researched. Addressing this gap is essential for a holistic understanding of the IOD's impact on the eastern Indian Ocean coastal system. Consequently, this study was conducted to analyze the influence of the IOD on SST and Chl-a in the Sunda Strait from 2006 to 2020, providing critical data for the sustainable management of marine and fishery resources

2. Materials and methods

The study focuses on the Sunda Strait, a strategic passage between Sumatra and Java. The specific sampling point for data extraction is located at 6° S and 105° 15' E (Figure 1). This location was selected to capture the dynamic water mass exchange between the Java Sea and the Indian Ocean.

The data utilized in this study spans a 15-year period from January 2006 to December 2020. Oceanographic parameters, specifically monthly SST and Chl-a concentrations, were retrieved from the Global Physics Reanalysis product available via the Copernicus Marine Service (https://marine.copernicus.eu/). The SST data possesses a spatial resolution of 0.083° (approximately 9 km), while the Chl-a data features a resolution of 0.25° (approximately 25 km). Additionally, the Dipole Mode Index (DMI) was employed to identify IOD phases throughout the study period. These climate index data were obtained from the NOAA Physical Sciences Laboratory (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/).

Data will be processed using Matlab software to analyze Time Series, Power Spectral Density (PSD), Pearson Correlation, Wavelet Coherence (WTC), and Cross Wavelet Transform (XWT). DMI data is processed with Microsoft Excel to separate IOD data according to its phase. The results of Time Series, PSD, Pearson Correlation, WTC, and XWT will be analyzed to understand the relationship between these parameters in the IOD phenomenon.

2.1 Pearson Correlation

The relationship between the studied variables was analyzed using the Pearson Correlation method. This approach quantifies the strength and direction of the linear relationship between two variables, yielding a correlation coefficient (r). A value approaching 1 or -1 indicates a strong linear association, while a value near 0 suggests no linear relationship (Sugiyono, 2000). To ensure the reliability of the results, the statistical significance of the correlation was assessed using p-values, with a significance threshold typically set at $p < 0.05$.

$$r = \frac{n\sqrt{XY} - (\sum X)(\sum Y)}{\sqrt{(n\sum X^2 - (\sum X)^2)(n\sum Y^2 - (\sum Y)^2)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

2.2 Power Spectral Density

Power Spectral Density (PSD) analysis was employed to identify the dominant periodicities and cyclical patterns of SST and Chl-a variability in the Sunda Strait. This analysis was performed using Welch's method in MATLAB, which improves the estimate of the spectral density by reducing noise in the signal. The process involved segmenting the 15-year time series into overlapping sections, applying a Hamming window to minimize spectral leakage, and averaging the periodograms. By transforming the time-domain data into the frequency domain, this method allows for a clear visualization of energy distribution across seasonal and interannual scales, providing insights into the recurring oceanographic processes that influence the marine ecosystem.

2.3 Cross Wavelet Transform

The expansion coefficients (*X_n)* derived from SPL anomalies and the Dipole Mode Index (DMI) are analyzed using the Cross Wavelet Transform (XWT). The XWT of two time series *X* and *Y* is defined as $W^{XY} = W^X W^{Y*}$, where * denotes the complex conjugate. In this study, we employed the Morlet mother wavelet with a dimensionless frequency of $\omega_0=6$, as it provides an ideal balance between time and frequency localization. To minimize edge effect artifacts, the time series were zero-padded prior to the transform. The Cone of Influence (COI) was applied to identify regions of the spectrum where edge effects become significant, ensuring that only the results unaffected by padding are interpreted. Statistical significance was tested against a red noise background at a 95% confidence level (Grinsted et al., 2004; Torrence & Compo, 1998).

$$\left(\frac{|W_n^X(s)W_n^{Y*}(s)|}{\sigma_X\sigma_Y} < p\right) = \frac{Z_v(p)}{v}\sqrt{P_k^X P_k^Y} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

with different angle averages a_m dari $a_i = 1, \ldots, n$ with the following equation:

$$X = \sum_{i=1}^{n} cos\ (a_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$Y = \sum_{i=1}^{n} sin\ (a_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

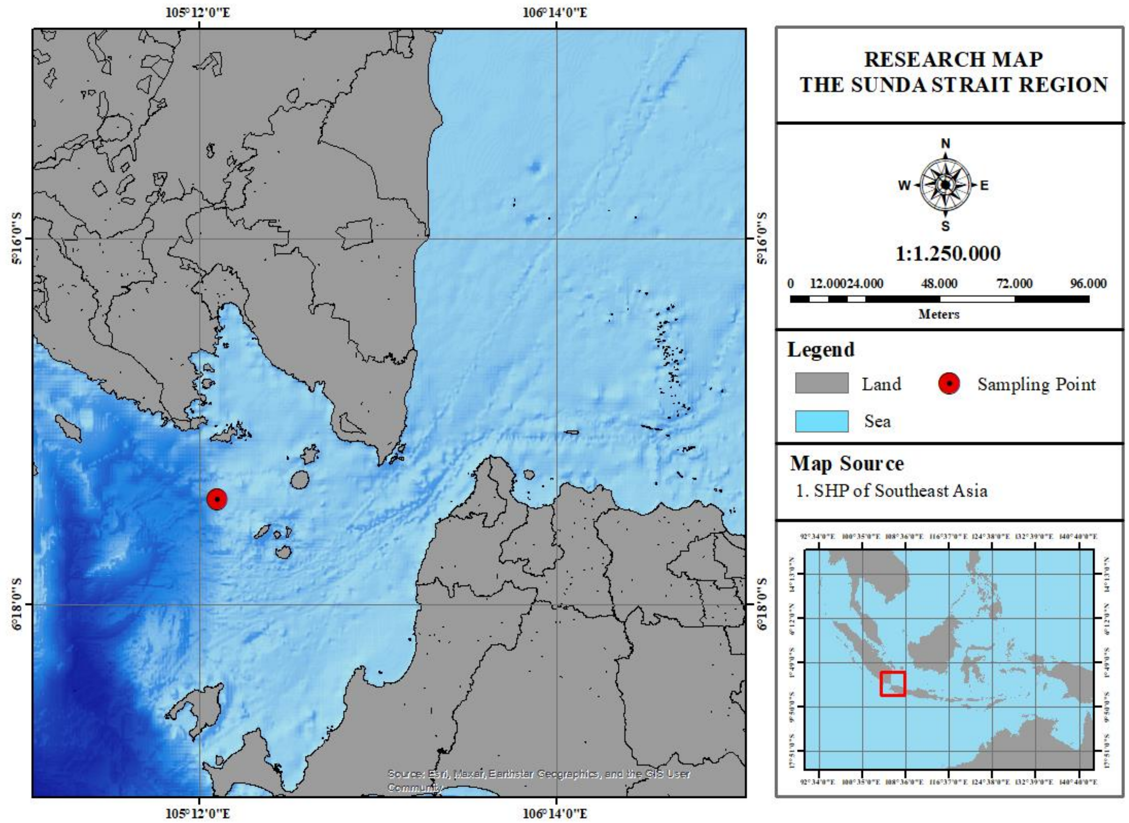

Figure 1. Research Map

Table 1. Interpretation of Correlation Coefficients (Sugiyono, 2000)

Coefficient Interval	Level of Influence
0.000-0.199	Very Low
0.200-0.399	Low
0.400-0.599	Currently
0.600-0.799	Strong
0.800-1.000	Very Strong

The phase difference between the SPL/Chlorophyll-a cycles and the DMI indicates the relative timing of their respective signal cycles. In the XWT plots, the relative phase relationship is represented by arrows: arrows pointing to the right indicate an in-phase relationship (positive correlation), while arrows pointing to the left indicate an anti-phase relationship (negative correlation). Furthermore, arrows pointing upward or downward indicate that one signal leads or lags the other. Specifically, an upward-pointing arrow indicates that the first dataset (e.g., DMI) leads the second (e.g., SPL) by 90^0 (a quarter cycle), whereas a downward-pointing arrow indicates a lag.

2.4 Wavelet Coherence

WTC is used to indicate regions with high overall strength. Another important measure is the extent to which WTC occurs in the time-frequency domain. Referring to Torrence and Webster (1999), wavelet coherence between two time series can be defined as follows:

$$R_n^2(s) = \frac{|S(W_{XYn}(s))|^2}{S(W_{Xn}(s))^2 \cdot S(W_{Yn}(s))^2} \quad \text{……..….……… (5)}$$

S refers to the smoothing operator. It is important to note that this definition is very similar to traditional correlation coefficients, and it is very useful for understanding wavelet coherence as a local correlation coefficient in the time-frequency domain. We express the smoothing operator (S) as follows.

$$S(W) = S_{scale}\left(S_{time}\left(W_n(s)\right)\right) \quad \text{………….……… (6)}$$

S_{scale} Referring to the smoothing along the wavelet scale axis, while S_{time} refers to the smoothing in the time domain. Typically, the smoothing operator is designed to have properties similar to the wavelet used. For the Morlet wavelet, the appropriate smoothing is provided by Torrence and Webster (1999).

$$S_{time}(W)_{|s=\left(W_n(s)*c_1\left(\frac{-2}{2^2}\right)\right)_{|s,}}$$

$$S_{time}(W)_{|s=\left(W_n(s)*c_2\Pi(0.6s)\right)_{|n.}} \quad \text{……………………..(7)}$$

3. Results and Discussion

3.1. Sea Surface Temperature, Chlorophyll-A, and Indian Ocean Dipole Conditions from 2006-2020

SST, Chl-a, and IOD for 15 years (2006-2020) in the Sunda Strait show temporal variations. Figure 2 shows the variation of the three variables to observe the interconnectedness of their patterns. The three variables show different patterns in different seasons and years.

SST fluctuations in the Sunda Strait over 15 years (2006-2020) are shown in Figure 2 and Table 2. SST in the Sunda Strait ranged from 27.63°C-30.55°C, with a mean SST of 29.13°C and a mode of 28.57°C (generally cooler). There were also fluctuations in Chl-a over the 15 years with values of 0.082 mg.L^{-1} - 3.611 mg.L^{-1}, a mean of 0.313 mg.L^{-1}, and a mode of 0.082 mg.L^{-1} (generally below the mean). Warm conditions, i.e. above-average SST, generally occur during the Western Season (DJF) to Transitional Season I (MAM). Under these conditions, chlorophyll-a values tend to be below average. Cold conditions, where the SST is below average, occur during the East Season (JJA) to the Second Transitional Season (SON). The low SST in this condition tends to be followed by an increase in chlorophyll-a values.

The IOD that occurred for 15 years generally showed normal conditions despite anomalous fluctuations. Positive IOD phases (IOD+) occurred in 2006, 2012, 2018, 2019, strong IOD+ in 2019. The negative IOD phase (IOD-) occurred in 2010, 2013, and 2016. In IOD+ years, there was a cooling of the SST in the Sunda Strait and an increase in chlorophyll-a. In contrast, in IOD- years, SST increased followed by a decrease in chlorophyll-a values.

Table 2. Descriptive Statistics of SST and Chlorophyll-a in the Sunda Strait (2006 – 2020)

Parameter	Min	Max	Mean	Mode	Unit
Sea Surface Temperature (SST)	27.63	30.56	29.14	28.58	°C
Chlorophyll-a (Chl-a)	0.08	3.61	0.31	0.08	mg.L^{-1}

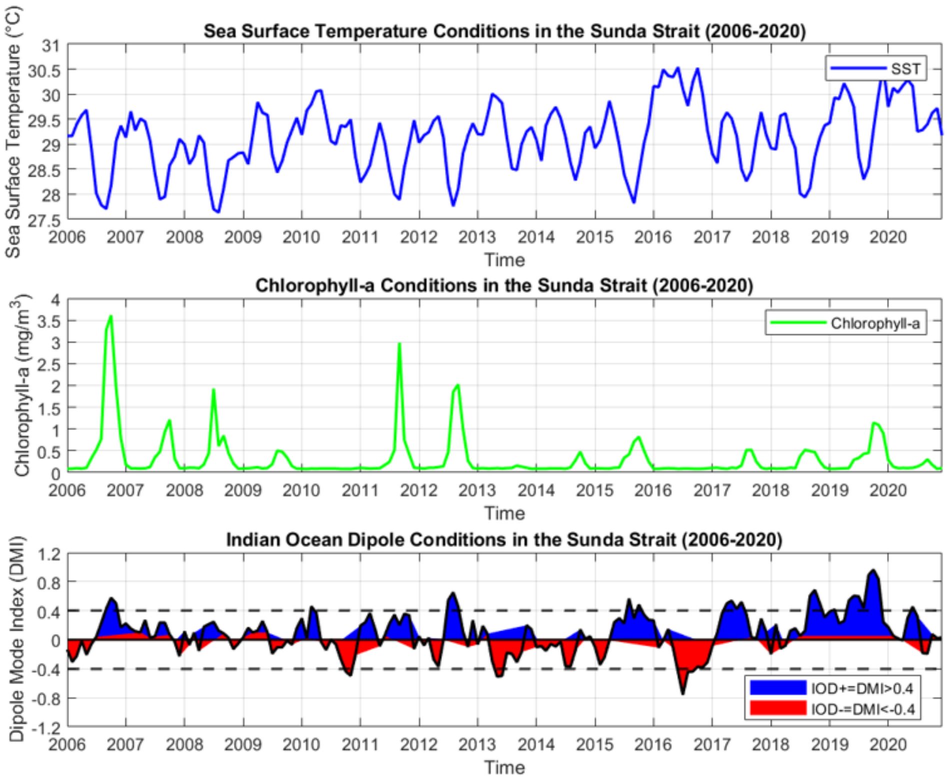

Figure 2. Temporal graph of Sea Surface Temperature, Chlorophyll-a , and Indian Ocean Dipole data over 15 years (2006-2020)

The data show a relationship between SST and chlorophyll-a. This is indicated by the inverse pattern/relationship of SST and chlorophyll-a. During warm periods (DJF and MAM), chlorophyll-a concentrations tend to be low. The opposite is shown in the cold period (JJA and SON), when SST is cooler, chlorophyll-a values tend to be higher. The decrease in SST in the East Season is caused by the intensity of the strong southeast monsoon winds, the peak of which occurs in August-September, causing upwelling in southern Java to the west, and reaching the waters south of West Java and around the Sunda Strait (Amri et al., 2013). Upwelling occurs because the southeast monsoon winds from Australia to Asia cause a decrease in pressure or air vacuum in the Sunda Strait and southern Java waters, which is then replaced by colder water masses from the lower layers (Teliandi et al., 2013; Kuswanto et al. 2017; and Wyrtki, 1961).

Temporally, the Indian Ocean Dipole (IOD) significantly governs the variability of Sea Surface Temperature (SST) and chlorophyll-a concentrations in the Sunda Strait through a well-defined causal chain. This process is initiated by an anomalous pressure gradient during IOD+ phases, which triggers stronger southeasterly (SE) wind anomalies. Based on composite time-series analysis, these intensified winds enhance offshore Ekman transport, subsequently driving robust upwelling events. This mechanical forcing brings cold, nutrient-rich water from the deeper layers to the surface, resulting in a marked decrease in SST and a corresponding surge in chlorophyll-a productivity. Conversely, during IOD− years, the weakening of SE winds and reduced wind stress curl lead to suppressed upwelling, warmer surface conditions, and lower nutrient availability. These findings are statistically supported by the strong correlation between high Dipole Mode Index (DMI) values and wind anomalies (e.g., ERA5 data), reinforcing the role of wind variability as the primary driver. This mechanism aligns with established literature by Saji et al. (1998) and Kunarso et al. (2005), which quantifies how IOD-driven wind stress regulates upwelling intensity and biological responses across the eastern Indian Ocean.

3.2. Analysis of Power Spectral Density of SST, Chlorophyll-A, and DMI

Based on Figure 3, the spectral variations indicate fluctuations occurring across different frequency ranges. The PSD analysis provides an overview of how the energy of the temperature signal is distributed across these frequencies, enabling the identification of patterns at various time scales. From the PSD graph, it is observed that both Sea Surface Temperature (SST) and chlorophyll-a signals exhibit similar spectral characteristics. This suggests that the variabilities of both parameters may be modulated by comparable energy drivers. The variability appears consistent with the influence of interannual phenomena (>12 months) such as the Indian Ocean Dipole (IOD). The dominant peaks within this period, as detailed in Table 3, support the possibility of IOD playing a role in the variability of SST and chlorophyll-a in the Sunda Strait. However, these variations are also regulated by annual (12 months) and seasonal (3–6 months) factors, such as the monsoon cycle (Fordhoshi et al., 2023).

3.3. Pearson Correlation Analysis of SST and Chlorophyll-A

Based on Figures 4, 5, 6 and 7, the results of the correlation analysis between SST - IOD and Chl-A - IOD during the period 2006 to 2020, it can be seen that there is quite an interesting relationship between these variables. The relationship between SST and IOD shows fluctuations in values that tend to be inversely associated, while Chl-A and IOD tend to be associated with each other in the same time span. The calculated Pearson correlation shows a correlation coefficient value of r which indicates the strength and direction of the relationship between the two variables.

The relationship between SST and DMI (Figure 4) shows the highest SST occurred in June 2016 at 30.54 C. This event is similar to 2010 and 2013, where the supposedly cold seasons such as JJA and SON tend to be warmer (above average). This is because it coincides with the negative IOD phenomenon. In this condition, the IOD phenomenon affects the value of SST. While the lowest SST (below average) occurred in 2006, 2012, 2018 and 2019 it coincided with the positive IOD phenomenon. According to Seprianto et al. (2016), stated that the Positive IOD phenomenon with warm SST in the Western Indian Ocean caused winds from Australia to blow with strong intensity towards the Western Indian Ocean.

Based on Figure 5, it can be seen that the relationship between SST and DMI values shows a relationship that can be expressed in a correlation value of -0.2627 with p values = 0.00036713 ($p < 0.05$). According to Sugiyono (2000), the correlation value between SST and IOD is included in the low category. The negative value in the correlation between SST and DMI values means that the relationship is negative or inversely proportional. This can be interpreted that if DMI increases, it will affect the decrease in the SST value and vice versa.

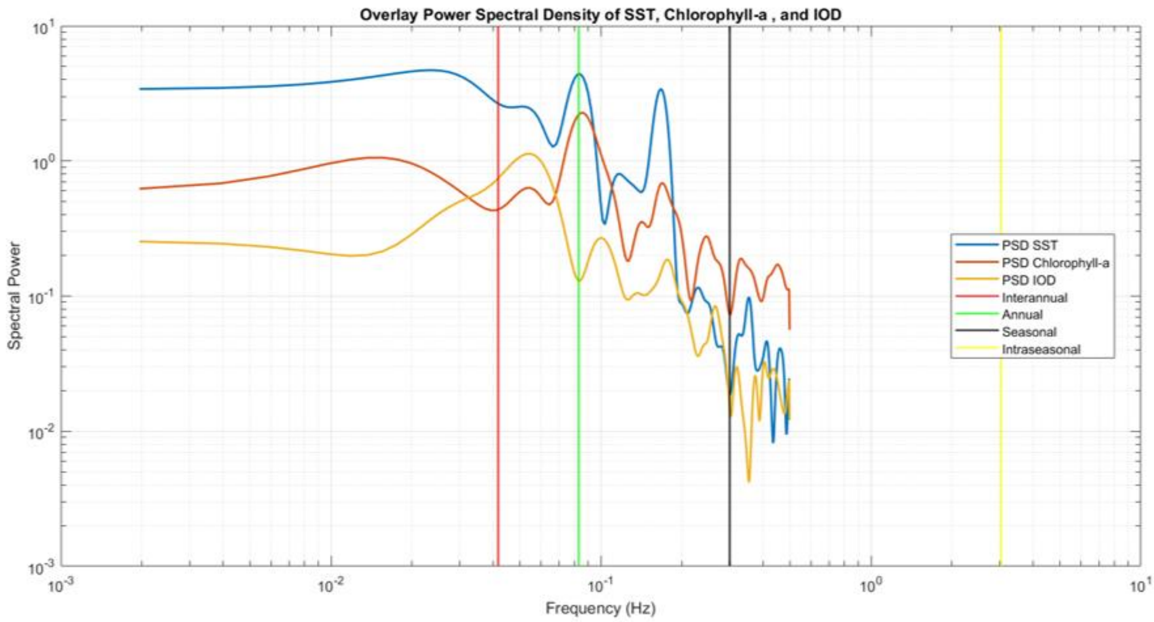

Figure 3. PSD Analysis of SST, Chlorophyll-a, and IOD over 15 years (2006-2020)

Table 3. PSD Analysis of Sea Surface Temperature and Chlorophyll-a in the Interannual Period

Phenomenon	Frequency Peak		Period		Power Spectrum Density	
	SST	Chlorophyll-a	SST	Chlorophyll-a	SST	Chlorophyll-a
Interannual (0,001953 Hz - 0,04102 Hz)	0,02348 Hz	0,01368 Hz	42,66 month (3,5 year)	73,15 month (6,09 year)	4,708 Hz	1,058 Hz

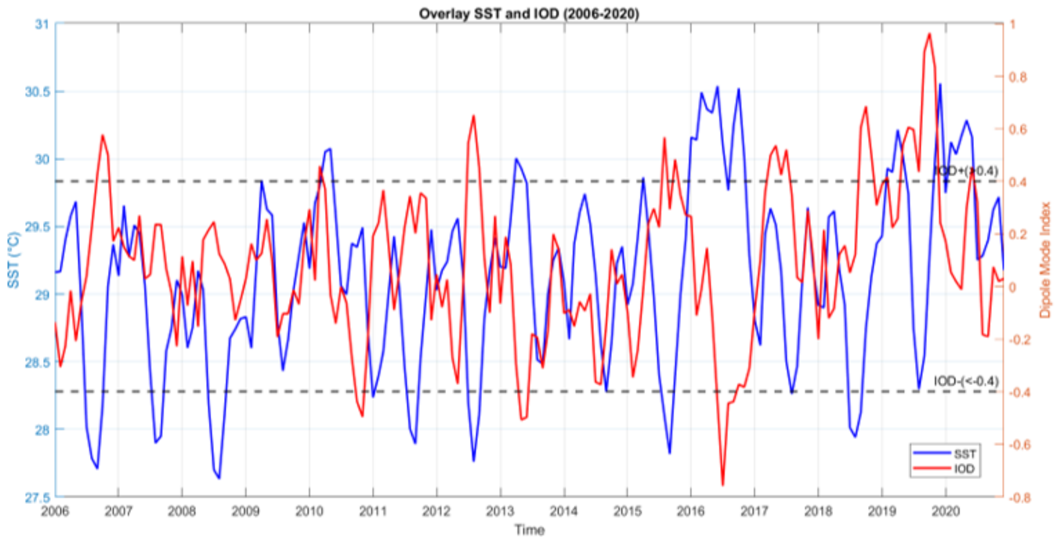

Figure 4. SST and IOD over 15 Years (2006-2020) in the Sunda Strait

The graph in Figure 6 shows a pattern that occurs in each year. This pattern shows that Chl-a values tend to increase every JJA. However, there was an unusual spike in Chl-a values in 2006 with a value of 3,611 mg.L^{-1}. This high Chl-a value coincided with the occurrence of IOD+. Positive IOD (DMI > 0.4) is often associated with an increase in Chl-a in some regions, which can be caused by changes in ocean water flow and increased upwelling that occurs during positive IOD phases. This upwelling process transports essential nutrients from deeper ocean layers to the surface, which supports the growth of phytoplankton, including Chl-a, which is a key indicator of phytoplankton presence in marine ecosystems.

However, there was also a significant spike in 2011. In that year, the IOD showed a normal phase, indicating that the high chlorophyll-a levels were more influenced by seasonal factors. This is in line with the results of the PSD analysis, which shows that chlorophyll-a is more influenced by seasonal phenomena. However, for a more accurate explanation, other factors such as upwelling, SST, or global phenomena such as the IOD, which can amplify or reduce chlorophyll-a levels, need to be considered.

Unusual decreases in Chl-A values were observed in 2010, 2013 and 2016. In these years, it appears that the season that should show high Chll-a, JJA, did not show an increase. These years coincided with the IOD phenomenon. During the negative IOD phase (DMI < -0.4), Chl-a tends to show a decrease, which can be caused by decreased upwelling activity or changes in ocean circulation patterns that affect nutrient distribution at the ocean surface.

The correlation analysis between Chl-a and DMI yielded a value of 0.3794 with *p* values = 0.00000015013 ($p < 0.05$) , which, according to Sugiyono (2000), falls into the moderate category. The positive correlation coefficient indicates a direct relationship between these variables, suggesting that higher Chl-a concentrations in the Sunda Strait typically coincide with positive IOD phases. However, it is crucial to interpret this as a local biological response to large-scale climate forcing rather than a causal influence; the IOD acts as an external driver that enhances upwelling and nutrient enrichment, thereby increasing Chl-a levels, whereas Chl-a variations do not influence the DMI index itself.

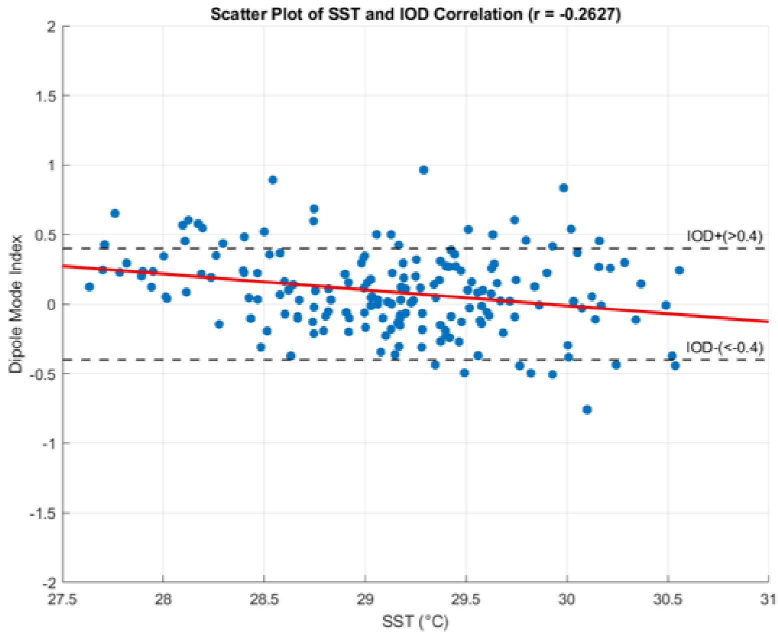

Figure 5. Results of Pearson Correlation Analysis between SST and IOD in the Sunda Strait

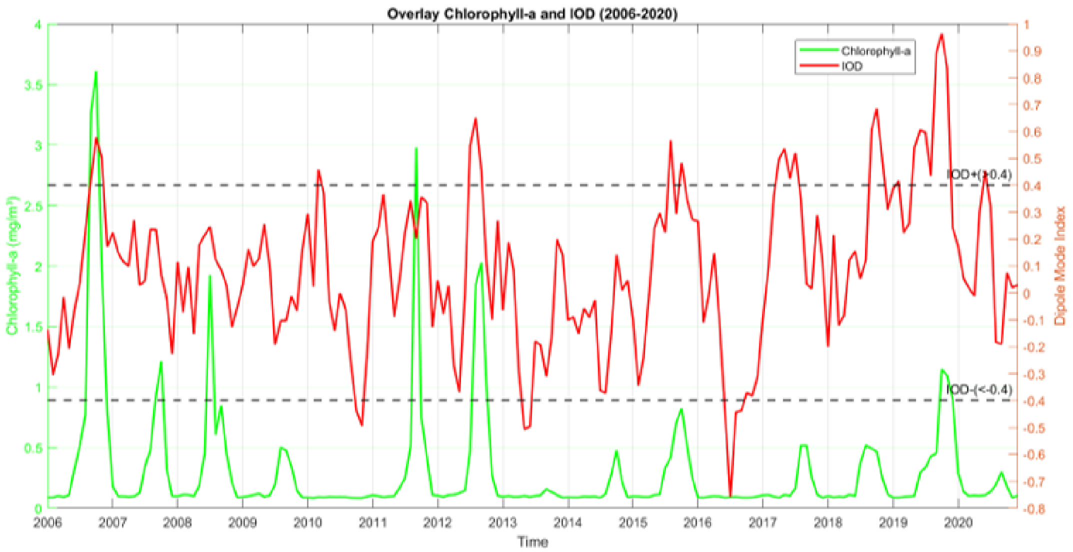

Figure 6. Chlorophyll-a and IOD over 15 years (2006-2020) in the Sunda Strait

The relatively low correlation between SST and the IOD index suggests that the Pearson correlation method may not fully capture the intricate relationship between these variables. Similarly, the correlation between Chlorophyll-a and the IOD, which falls into the moderate category, does not fully reflect the anticipated impact given the Sunda Strait's proximity to the IOD's core region. This discrepancy is likely due to the spatial complexity of the strait and multi-factor controls, such as local monsoon winds and tidal mixing, which can mask the IOD signal. Furthermore, oceanographic responses to climate forcing often exhibit non-linearities and time-lagged effects that a simple linear correlation cannot detect. Therefore, advanced analyses using Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) are necessary to resolve these relationships across different time scales and identify potential phase lags.

3.4. Analysis of Power Spectral Density of SST, Chlorophyll-A, and DMI

The XWT analysis between SST and the IOD reveals a significant anti-phase relationship during the inter-annual period, particularly evident between 2015 and 2018 (Figure 10). Established data records show positive IOD events in 2006, 2012, 2018, and 2019, and negative events in 2010, 2013, and 2016. The XWT results demonstrate an inverse relationship (high common power in opposite phases) between these variables across different time spans, specifically within the lower frequency bands of 16–32 months and >32 months, consistent with the Power Spectral Density (PSD) findings.

The XWT results for the relationship between Chl-a and the IOD in the Sunda Strait (2006–2020) also exhibit a clear pattern associated with IOD oscillations (Figure 11). These findings indicate a substantial IOD influence on chlorophyll-a dynamics, with high-power concentrations at the 4- to 16-month timescales. Stronger interactions occur during positive IOD phases (2006 and 2012) within the 8–16 month period. Conversely, during negative IOD phases (2010, 2013, and 2016), the intensity of this relationship diminishes, reflecting suppressed upwelling and rising SST, which restricts nutrient supply to phytoplankton. To verify whether the high-power regions identified in the XWT represent a statistically significant correlation, a Wavelet Coherence (WTC) analysis was employed. The coherence results between SST and DMI confirm a robust correlation (indicated by the orange-yellow contours) maintained during the 16–32 month period. This WTC validation reinforces the conclusion that IOD variations exert a direct influence on the thermal and biological conditions of the Sunda Strait through a consistent inverse relationship.

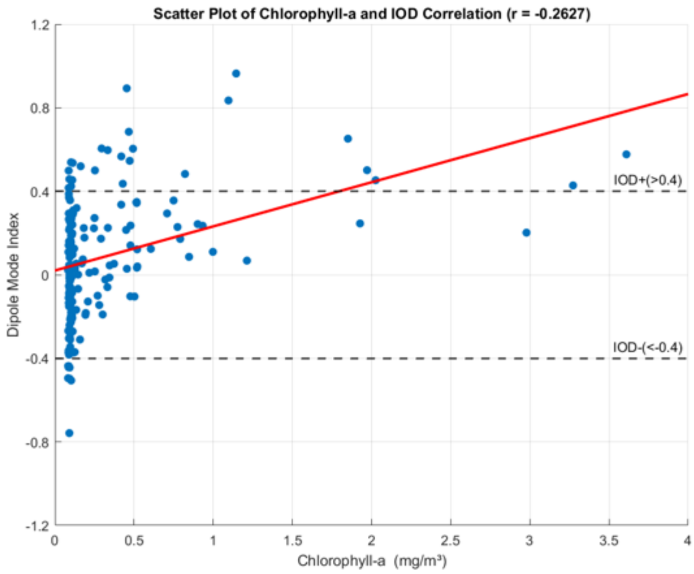

Figure 7. Results of Pearson Correlation Analysis between Chlorophyll-a and IOD in the Sunda Strait

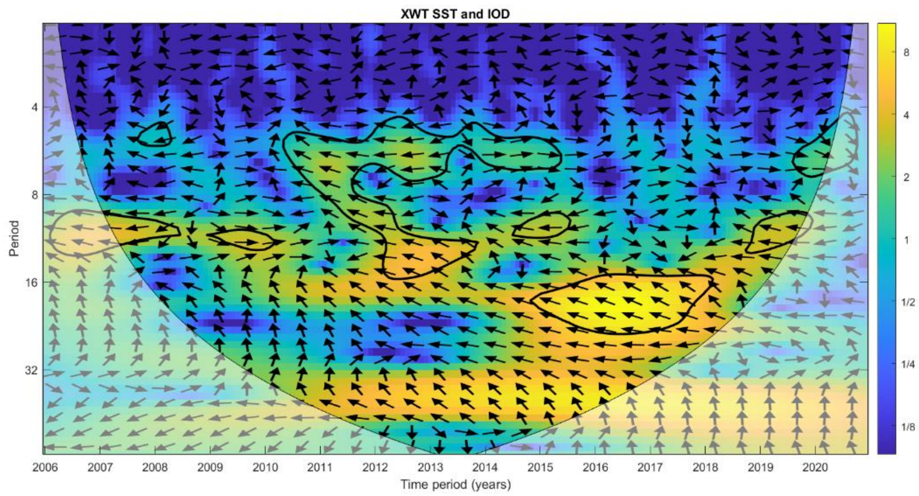

Figure 8. Results of XWT Analysis on SST and IOD

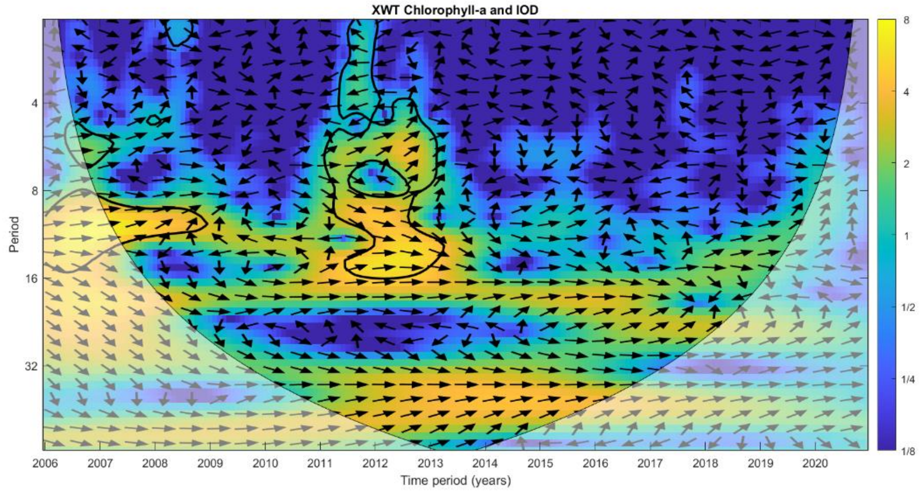

Figure 9. Results of XWT Analysis on Chlorophyll-a and IOD

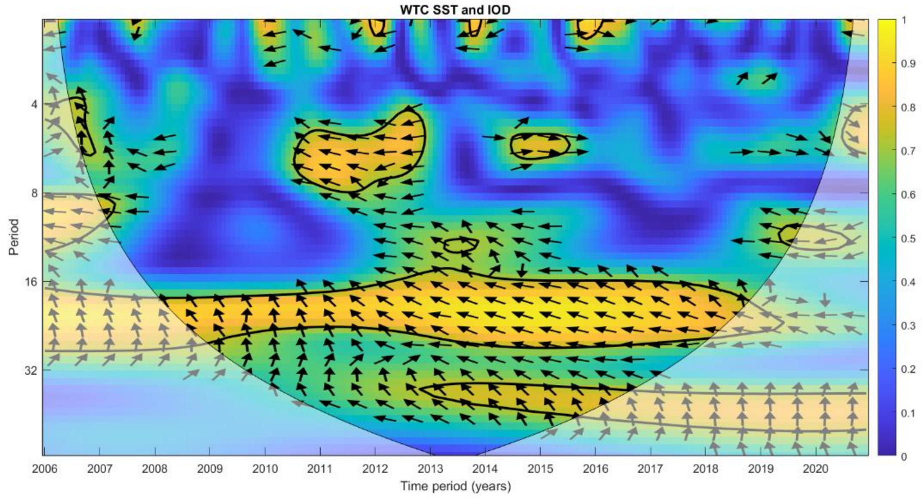

Figure 10. Results of WTC Analysis on SST and IOD

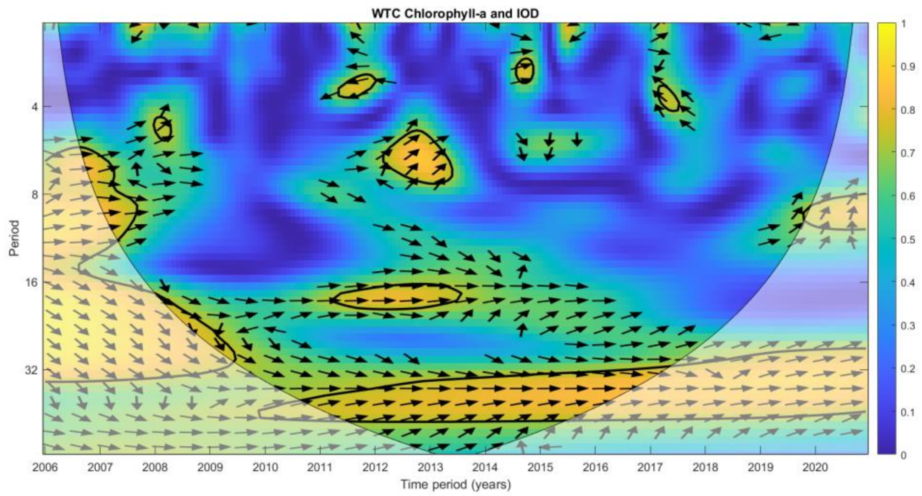

Figure 11. Results of XWT Analysis on Chlorophyll-a and IOD

Figures 10 and 11 show the results of the WTC analysis between SST-IOD and Chl-a - IOD, for the time period from 2006 to 2020. The horizontal axis shows the time period (years) from 2006 to 2020, while the vertical axis depicts the period in years (ranging from 4 to 32 months). The colors in the spectrum indicate the level of coherence between the two variables (0-1), with blue indicating lower coherence, while yellow and orange indicate higher or more significant coherence.

In Figure 10, the results of the SST and DMI analysis show that there is significant coherence during the 16-32 and >32 month periods. The phase direction between SST and DMI shows the opposite direction, indicating an inverse relationship between SST and the IOD phenomenon. This coherence is more evident in 2006-2019, where the Interannual phase (IOD) has a greater influence on SST in the 16-32 month period with a value of 0.9 (very strong). The years 2013-2020 also display strong coherence results with a value of 0.8 in the >32 month period.

Previous XWT results (Figure 8) and PSD analysis also support these findings, where coherence between SST and IOD is more pronounced on the interannual timescales of 16-32 months and >32 months, indicating that the IOD phenomenon affects SST and nutrient distribution in the Sunda Strait on longer timescales. This was also reported by Widianti and Pahlevi (2020), who stated that SST and Chl-a are influenced by the interannual phase (IOD). The results stated that the relationship between SST and Chl-a was stronger in the positive IOD phase, where increased upwelling supported higher Chl-a concentrations. This suggests that the interannual phase influences the SST values more.

The results of WTC analysis of the relationship between Chl-a and the IOD in the Sunda Strait during 2006-2020 are shown in Figure 11. It can be seen that there is a significant correlation in phase between the two variables in some periods, namely around 8-32 and >32 months. In these periods, the coherence between IOD and chlorophyll-a shows a close pattern with a value of 0.9 (2006-2008) in the 8-32 month period and 0.8 (2010-2020) in the >32 month period. These values reflect the strong influence of the IOD (Interannual) phenomenon on nutrient availability and marine primary productivity in the Sunda Strait. Results on the WTC analysis between Chlorophyll-a and IOD showed a strong coherence in the interannual (IOD) phase. During negative IOD phases, especially in 2016, SST tends to be higher, leading to decreased upwelling and reduced chlorophyll-a concentrations in the Sunda Strait waters.

4. Conclusion

This study characterizes the variability of SST and chlorophyll-a (Chl-a) in the Sunda Strait over a 15-year period (2006–2020). Recurring annual patterns were observed, with SST ranging from 27.63°C to 30.55°C (mean 29.13°C) and Chl-a fluctuating between 0.082 and 3.611 mg.L^{-1} (mean 0.313 mg.L^{-1}). While Pearson correlation results indicate weak-to-moderate linear relationships, frequency-domain analysis reveals that inter-annual phenomena, specifically the IOD, contribute significantly to parameter anomalies.

The PSD analysis confirms that the IOD influences the variability of SST and Chl-a, although these variations remain primarily governed by seasonal monsoon cycles. Crucially, XWT and WTC analyses identify a robust relationship within the 16–32 month band, characterized by distinct phase dynamics. The results show an anti-phase relationship between IOD and SST, whereas IOD and Chl-a exhibit an in-phase alignment with a discernible time lag. These findings suggest that positive IOD phases drive SST cooling and enhance chlorophyll-a concentrations in the Sunda Strait, likely through intensified upwelling processes.

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