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ENSO and IOD Effects on Sea Surface Temperature and Chlorophyll-a in the Semi-Enclosed Waters: Case Study of Bone Bay, Indonesia

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ABSTRACT

Bone Bay, a semi-enclosed marine region within the Coral Triangle, holds significant potential for fisheries. Understanding oceanographic parameters, particularly sea surface temperature (SST) and chlorophyll-a (Chl-a), is crucial for sustainable fisheries management. This study investigated the influence of ENSO and the Indian Ocean Dipole (IOD) on SST and Chl-a variability in Bone Bay using Niño3.4 and Dipole Mode Index (DMI) data from NOAA (2010–2020). SST and Chl-a were analyzed through remote sensing techniques using Aqua-MODIS satellite imagery and spatial-temporal methods. Additionally, statistical analysis was conducted using the relationship analysis with cross-correlation method to evaluate the relationship between ENSO, IOD, and oceanographic parameters. The results indicated that extreme ENSO and IOD events, particularly in 2015–2016, do not exhibit a strong correlation with Chl-a variability. The Chl-a anomaly correlation values was 0.03 for ENSO and was 0.09 for IOD. Similarly, SST anomalies show a weak correlation with ENSO at 0.04 and a correlation with IOD at 0.24. The semi-enclosed nature of Bone Bay likely buffers it from large-scale climatic events, with local hydrodynamic factors playing a more dominant role. These findings provide critical insights for fisheries resource management in semi-enclosed waters and emphasize the need for localized oceanographic studies to inform policy decisions.

INTRODUCTION

Bone Bay is one of the most biologically productive fishing areas within the Coral Triangle, located in the central Indonesian waters **(Putri *et al.*, 2018)**. This region is influenced by complex oceanographic interactions, including monsoonal currents, tidal mixing, and wind-driven upwelling, which significantly affect sea surface temperature (SST) and chlorophyll-a (Chl-a) concentrations **(Gordon, 2005; Qu & Liu, 2020; Zainuddin *et al.*, 2020; Piedracoba *et al.*, 2024)**. Understanding SST and Chl-a variability is crucial, as these parameters directly impact marine ecosystems and fishery productivity **(Zainuddin *et al.*, 2017; Hidayat *et al.*, 2019)**.

ENSO (El Niño-Southern Oscillation) and the Indian Ocean Dipole (IOD) are among the most influential climate phenomena affecting oceanographic conditions globally. ENSO is characterized by periodic fluctuations in sea surface temperatures and atmospheric pressure across the equatorial Pacific, while IOD is defined by temperature differences between the western and eastern Indian Ocean **(Trenberth, 1997; McPhaden, 2012)**. These large-scale climatic events have been linked to significant variations in SST and Chl-a in open water systems, such as the Bali Strait **(Sambah *et al.*, 2021)** and the Makassar Strait **(Baharuddin *et al.*, 2022)**.

However, studies on semi-enclosed waters like Bone Bay remain limited. Unlike open water systems, semi-enclosed waters are influenced by local oceanographic dynamics, such as restricted water exchange, coastal upwelling, and local wind patterns, which may buffer the effects of ENSO and IOD **(Trenberth, 1997; Zhou & Yu, 2006; Yu & Zhou, 2007; Susanto *et al.*, 2012)**. Understanding whether these large-scale climatic events significantly impact SST and Chl-a in semi-enclosed waters is crucial for fisheries management and marine conservation **(Arleston *et al*., 2016; Holbrook *et al.*, 2020)**.

Previous studies have extensively examined ENSO and IOD impacts in open water regions **(Purwandari *et al.*, 2019; Kumar *et al.*, 2024)**. However, limited research has investigated how these climate phenomena influence SST and Chl-a in semi-enclosed waters, where localized hydrodynamic processes may dominate.

Therefore, this study aimed to analyze the variability of SST and Chl-a in Bone Bay from 2010 to 2020 and assess their relationship with ENSO and IOD. By utilizing satellite remote sensing data and statistical analysis, this research seeked to determine whether large-scale climate drivers significantly influence oceanographic conditions in semi-enclosed waters. The findings are expected to contribute to sustainable fisheries management by improving the understanding of climate-related oceanographic variability in coastal ecosystems.

MATERIALS AND METHODS

1. Study area

This study was conducted in Bone Bay, located in the central Indonesian waters (Fig. 1). Bone Bay is a semi-enclosed water, directly connected to the Flores Sea, making it an important site for marine productivity and fisheries. Due to its geographical setting, oceanographic conditions in Bone Bay are influenced by both large-scale climatic phenomena (ENSO and IOD) and local hydrodynamic processes (coastal upwelling, seasonal wind patterns, and freshwater discharge).

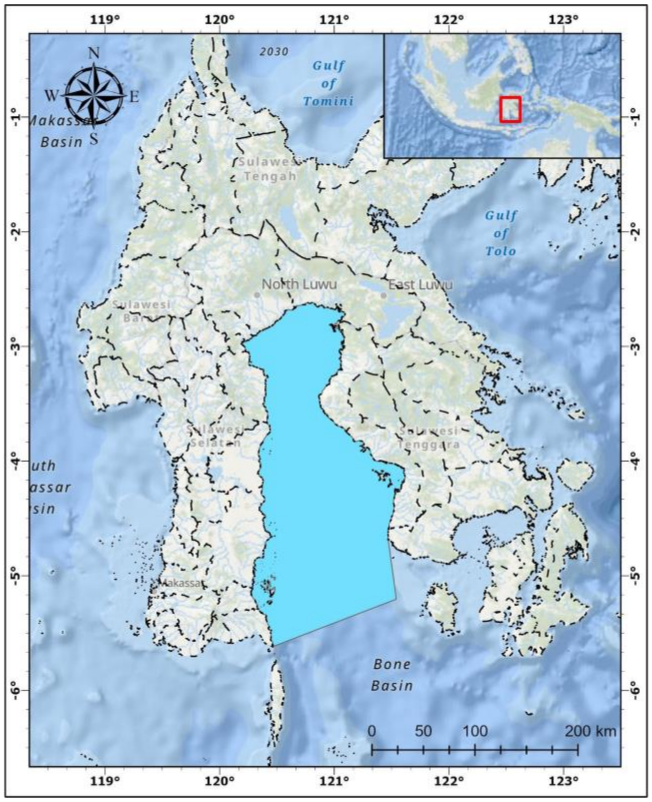

Fig. 1. Research location

2. Data Collection

2.1 Climate index: Niño3.4 index

The Niño3.4 index was conducted through the NOAA (National Oceanic and Atmospheric Administration) Climate Prediction Center (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Niño34/). The Niño3.4 Index data used in this study were obtained from NOAA's monthly datasets covering the period from 2010 to 2020, with a spatial resolution of 2° × 2° in the central and eastern equatorial Pacific Ocean (5°N–5°S, 170°W–120°W). NOAA uses satellite-based remote sensing and *in-situ* oceanographic measurements to monitor ocean-atmosphere interactions, including sea surface temperature (SST) anomalies. El Niño refers to a phenomenon where SSTs in the central and eastern equatorial Pacific Ocean increase, leading to cooler-than-normal SSTs in Indonesia. In contrast, La Niña describes a cooling of SST in the equatorial Pacific, resulting in warmer SSTs in Indonesia. Both phenomena are identified when the Niño3.4 Index reaches a threshold of +0.5°C for El Niño and -0.5°C for La Niña, sustained for at least five consecutive months.

2.2 Climate index: Dipole mode index (DMI)

The intensity of the Indian Ocean Dipole (IOD) was measured by the Dipole Mode Index (DMI), which reflects the gradient of sea surface temperature (SST) anomalies between the western equatorial Indian Ocean (50-70°E and 10°S-10°N) and the southeastern equatorial Indian Ocean (90-110°E and 10°S-0°N). The DMI data were accessible through NOAA's Climate Prediction Center (https://psl.noaa.gov/data/timeseries/DMI). Similar to the ENSO phenomenon, DMI was monitored over a period of five consecutive months. A DMI value of +0.5°C indicates a positive IOD (IOD+), while a value of -0.5°C signifies a negative IOD (IOD-).

2.3 Satellite remote sensing data

All research data used were oceanographic data obtained using the Aqua satellite with the Moderate Resolution Imaging Spectroradiometer (Aqua-MODIS) sensor. The oceanographic data used were sea surface temperature (SST) and chlorophyll (Chl-a) collected from data provider Ocean Color (http://oceancolor.gsfc.nasa.gov). Data selection uses the facilities of the Google Earth Engine with daily temporal resolution and 4km per pixel spatial resolution. After cropping the data in ArcGIS, the data were combined into monthly data using Microsoft Excel.

3. Data Analysis

3.1 Anomaly analysis

The anomaly method was used to evaluate the change in oceanographic conditions from 2010 to 2020 in the Bone Bay. Satellite imagery data identified decreasing (negative anomaly) and increasing (positive anomaly) oceanographic parameters relative to normal conditions. The equation analysis of the SST anomaly and Chl-a anomaly formulas was used and implemented in Microsoft Excel, and a monthly time series graph for ten years was created on Origin 8.5.1 software. The equation used for the calculation of anomaly oceanographic parameters **(Putri & Zainuddin, 2019)** was as follows:

$$\delta_{ij} = T_{ij} - T_i$$

Where, δij is anomaly of oceanographic parameters in a month i and year j, Tij is oceanographic parameter factor in month I, and Ti is oceanographic parameter factor value in a month i and year j.

3.2 Relationship analysis with cross-correlation

Cross-correlation, a correlation between two variables in the form of a time series with the same time and a time lag, was used to assess the association between variables using open-source RStudio 4.0.5 software. The two variables in the k-lag will be most closely related when there is a significant correlation between them. The confidence interval utilized for this analysis was 95%. The correlation value was considered significant if the *P*-value was less than 0.05 (Table 1). The cross-correlation calculation formula used is as follows:

$$r_{xy} = \frac{(\sum xy) - \sum(x) . \sum(y)}{\sqrt{n(\sum x)^2 - (\sum x)^2}\sqrt{n(\sum y)^2 - (\sum y)^2}}$$

Where, r is coefficient of cross-correlation, x is the input data, and y is the output data.

Table 1. Cross-correlation coefficient relations correlation

Correlation value	Interpretations
0.0 - 0.2	Very Low
0.2 - 0.4	Low
0.4 - 0.7	Strong
0.7 - 1.0	Very Strong

Source: (**Wijaya *et al.* 2020)**

3.3 Definition of Niño3.4 and DMI

The Dipole Mode Index (DMI) was identified through continuous monitoring over a period of five consecutive months. According to the DMI assessment criteria, a value of +0.5°C indicates a positive IOD (IOD+), while a value of -0.5°C signifies a negative IOD (IOD-). Similarly, the Niño3.4 index was used to identify El Niño and La Niña events, with a value of +0.5°C indicating El Niño and a value of -0.5°C indicating La Niña.

RESULTS AND DISCUSSION

1. Variability of sea surface temperature (SST)

Sea surface temperature (SST) is a critical physical parameter that plays a significant role in the detection and monitoring of various marine organisms **(Abudaya, 2013)**. Additionally, SST serves as an essential variable for identifying oceanic and climatic phenomena, including the occurrence of El Niño and La Niña events.

The analysis of SST data (Fig. 2) reveals a distinct seasonal pattern, with lower temperatures occurring at the beginning and end of the year, and a notable cooling phase from June to September. Over the 11-year study period (2010–2020), this recurring trend remains consistent, with SST increasing in early months and reaching its peak around March, followed by a gradual decline towards mid-year. The lowest recorded SST was in August 2015 at 28.18°C, while the highest occurred in March 2016 at 31.53°C (Fig. 3).

These findings align with previous research by **Rosalina *et al.* (2024)** which also reported the lowest SST values during the mid-year period (June–September), with temperatures dropping to approximately 28.70°C. This mid-year cooling phase is strongly indicative of upwelling events, where surface waters are displaced, allowing cooler, nutrient-rich waters from deeper layers to rise. Upwelling plays a crucial role in enhancing marine productivity and directly influences ecosystem dynamics **(Nguyễn *et al.*, 2020)**.

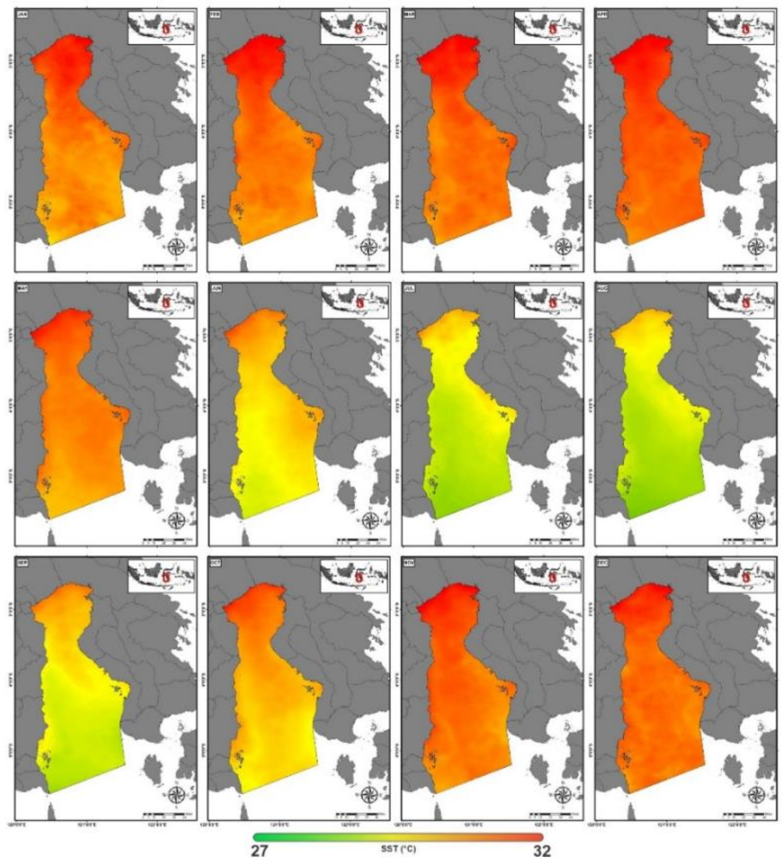

Fig. 2. Average spatial variation of SST January - December 2010 to 2020

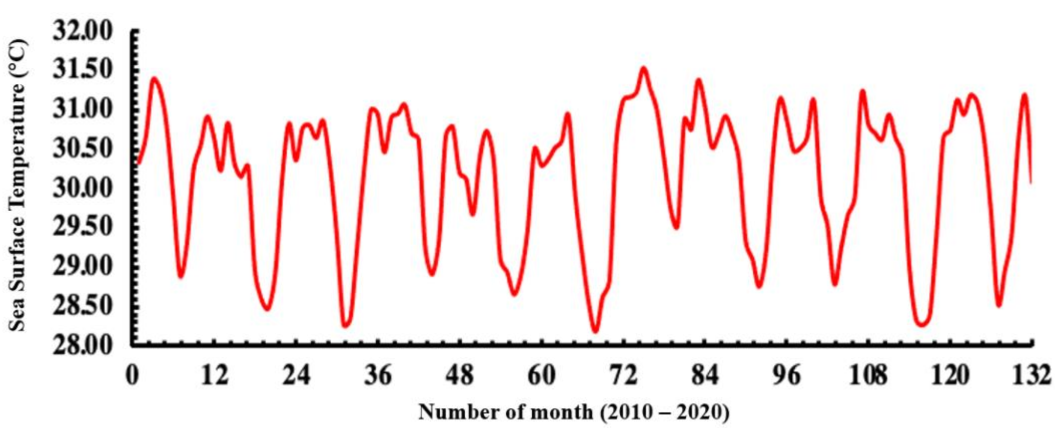

Fig. 3. Average temporal variation of SST 2010 to 2020

Furthermore, Fig. (3) highlights a recurring annual SST cycle, demonstrating consistent seasonal fluctuations. However, while this pattern remains largely stable, certain years exhibit more pronounced variations, likely influenced by broader climatic phenomena. Despite these fluctuations, the long-term SST trends in the study area appear to be minimally impacted by global climatic events such as ENSO, suggesting that local oceanographic processes may play a more dominant role in SST regulation.

2. Variability of Chlorophyll-a (Chl-a)

Based on the visualization results, the average value of Chl-a concentrations can be seen if the Chl-a variation has a not-too-conspicuous pattern. This is very different from what happens at SST. However, this parameter is considered essential for analysis because it is also closely related to the presence of aquatic organisms **(Safruddin *et al.* 2018)**.

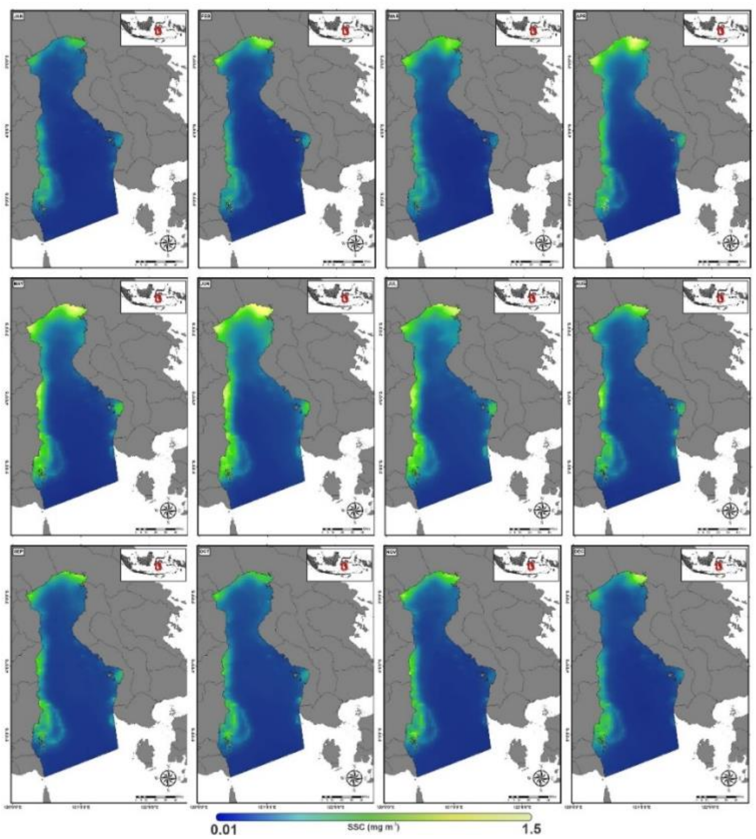

Fig. 4. Average spatial variation of Chl-a January - December 2010 to 2020

Fig. (4) shows that in the middle of the year, namely from April to July, spatially, there is an expansion of areas that have high Chl-a concentration values. This event is supported by temporal observations for 11 years (2010 – 2020), which show that the highest Chl-a value was in April 2016 at 0.62mg m^{-3}, while the lowest average Chl-a value occurred in February 2011 at 0.17mg m^{-3} (Fig. 5).

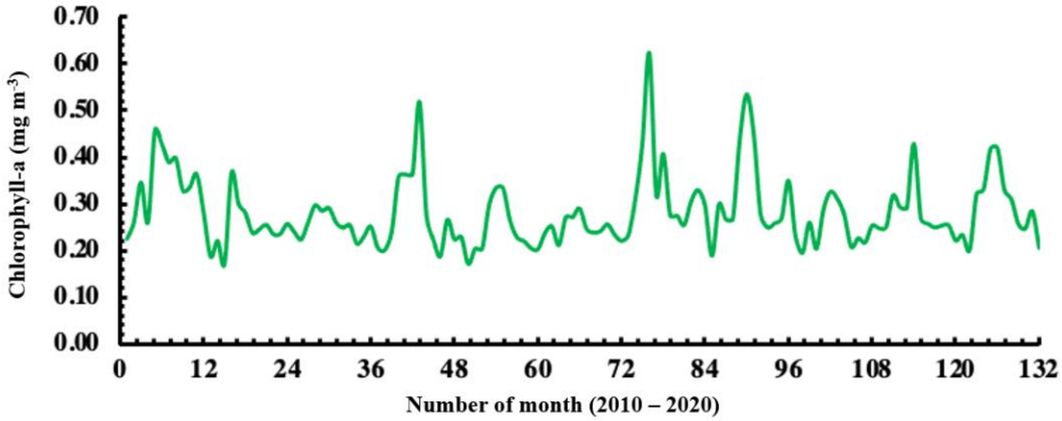

Fig. 5. Average temporal variation of Chl-a 2010 to 2020

The analysis of the graph (Fig. 5) reveals that chlorophyll-a (Chl-a) does not exhibit a consistent pattern of increase or decrease throughout the observation period. This lack of consistency suggests that Chl-a variability is influenced by factors beyond the seasonal cycle. Unlike parameters such as SST, which demonstrate clear seasonal fluctuations, the irregularity in Chl-a trends points to the role of external drivers, such as local wind patterns, nutrient availability, ocean currents, or episodic climatic phenomena, in shaping Chl-a distribution.

The absence of a distinct seasonal signal in Chl-a further highlights the complexity of oceanographic processes affecting chlorophyll concentrations, emphasizing the need for more detailed investigations into the interplay of environmental variables.

3. Relation between ENSO-IOD with Anomaly of SST and Chl-a

An 11-year temporal analysis (2010–2020) of Niño 3.4 index data reveals distinct ENSO events (Fig. 6). A prolonged El Niño occurred from November 2014 to April 2016, with an exceptionally strong peak in November 2015 (2.57°C). Although El Niño recurred multiple times within the study period, most events remained moderate, around 0.5°C **(Iskandar *et al.*, 2018)**. Similarly, La Niña events were observed, with an extreme phase occurring from June 2010 to May 2011, reaching its lowest value in January 2011 (-1.7°C). Another La Niña phase was recorded from August 2011 to February 2012, with the lowest value of -1.09°C in November 2011.

The Dipole Mode Index (DMI) analysis (Fig. 6) highlights an extreme positive Indian Ocean Dipole (IOD+) event from May to November 2019, with the highest value of 0.964°C. Conversely, the lowest extreme DMI value occurred in July 2019 (-0.758°C). However, since a persistent five-month duration is required to classify a negative IOD (IOD−) event, this criterion was not met during the study period. These classifications are based on standard thresholds, where El Niño and IOD+ are identified at ≥0.5°C, while La Niña and IOD− are defined at ≤ -0.5°C.

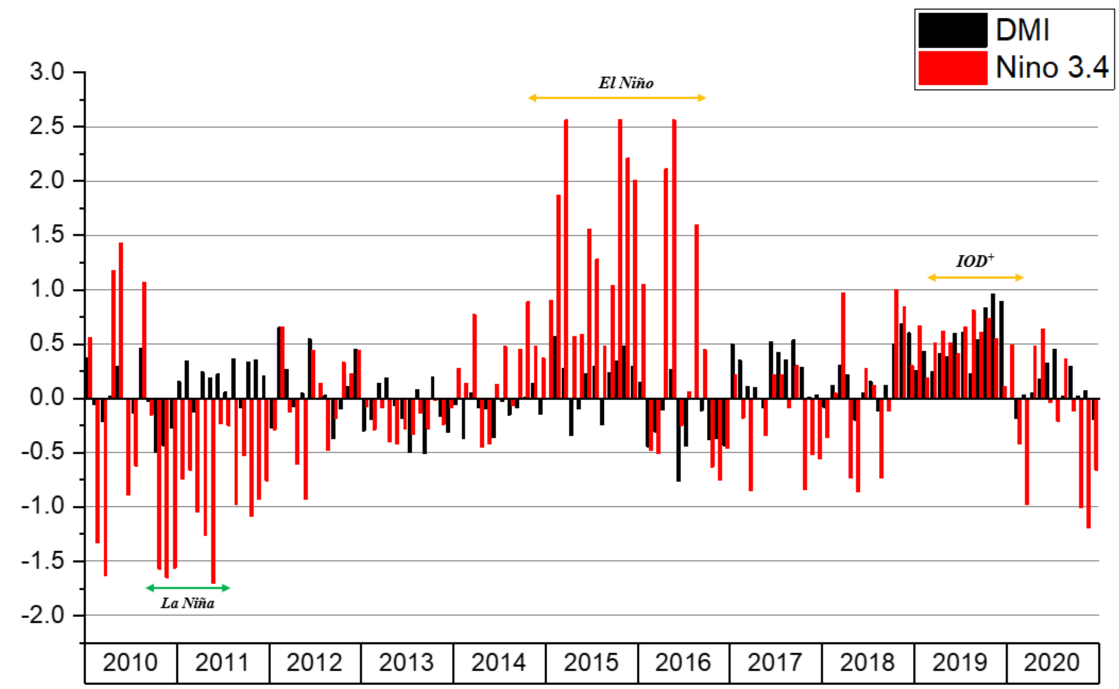

Fig. 6. Variation of Niño3.4 Index (red) and DMI (black) data from 2010 to 2020. The 0.5 line is the boundary line to identify the El Niño and IOD+, the -0.5 line to boundary La Niña and IOD- criteria

Despite these variations in ENSO and IOD, SST and Chl-a anomalies in Bone Gulf do not exhibit strong responses to these climate events (Fig. 7). The SST anomaly follows a stable annual cycle, with no significant deviations during El Niño or La Niña years. Meanwhile, Chl-a anomalies show some correlation with negative IOD (IOD−) events (Fig. 7), but overall, neither ENSO nor IOD strongly influences SST and Chl-a dynamics. This suggests that other oceanographic factors, such as wind-driven currents, may have a more dominant role in shaping the semi-enclosed waters of Bone Gulf.

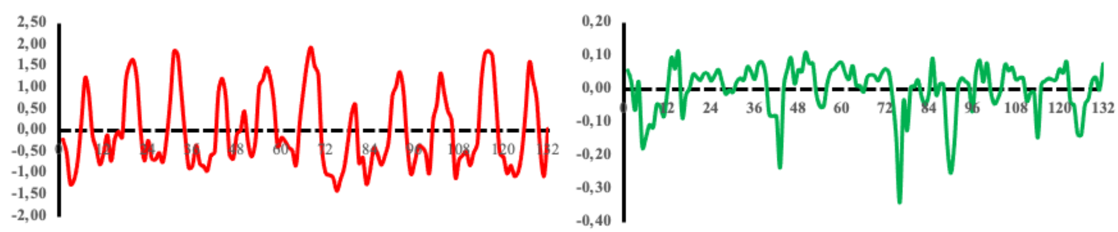

Fig. 7. Mean variation of SST (red) and Chl-a (green) anomaly data from 2010 to 2020

These findings align with **Kumar *et al.* (2024)**, who noted that semi-enclosed regions are generally less affected by ENSO compared to open-ocean systems. In contrast, regions like the Bali Strait exhibit stronger responses to ENSO, although the associated SST and Chl-a anomalies tend to be weaker **(Sambah *et al.*, 2021)**.

Despite the weak ENSO signal in Bone Gulf, strong El Niño events are typically associated with negative SST anomalies and positive Chl-a anomalies, indicating enhanced upwelling in certain areas. Conversely, the IOD appears to have a more pronounced effect on SST and Chl-a variability. Positive IOD (IOD+) events correspond to negative SST anomalies and positive Chl-a anomalies, while negative IOD (IOD−) events are linked to positive SST anomalies and negative Chl-a anomalies. These patterns highlight the greater role of the IOD in modulating regional oceanographic conditions compared to ENSO **(Thandlam *et al.*, 2022)**.

4. Correlation model and result

Based on the analysis of the four variables: ENSO, DMI, Chl-a, and SST anomaly can be concluded that none of these parameters have any relationship with each other (Fig 8 & Table 2). This result is supported by the correlation test using the Pearson method with *P*-value analysis. The factor most likely influencing this is the location and characteristics of the semi-enclosed waters, which are significantly different from open waters. Additionally, the location of the Bone Bay, surrounded by a range of mountains, makes the seasonal variations in this area highly dynamic.

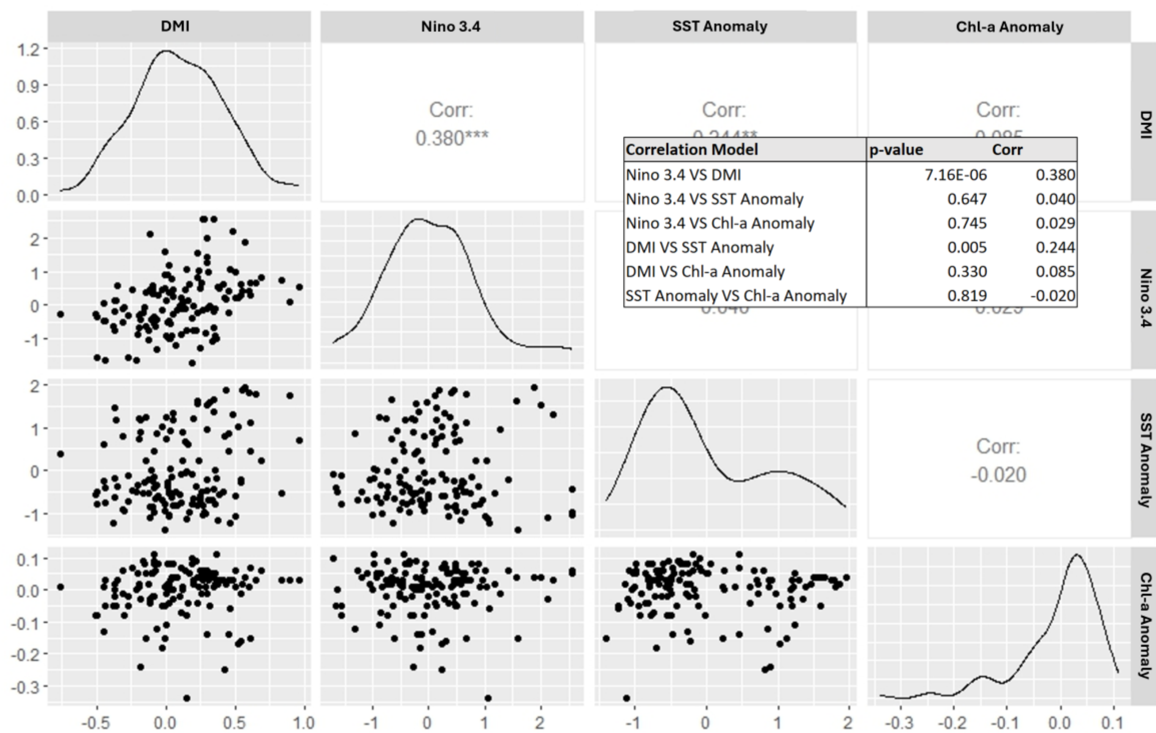

Fig. 8. Correlations plot of Niño3.4 Index, DMI, Chl-a anomaly, and Chl-a anomaly

Nevertheless, this study focuses solely on semi-enclosed waters, where, according to many references, ENSO and IOD events are generally of great concern due to their significant influence on large or open waters **(Dewi *et al.*, 2018; Sambah *et al.*, 2021)**. Related studies, such as those conducted in the Makassar Strait, have shown a considerable impact on the dynamic properties of SST and Chl-a parameters **(Hidayat *et al.*, 2021)**, which are even closely linked to fish catch production **(Baharuddin *et al.*, 2022)**.

Table 2. Correlations of Niño3.4 Index, DMI, SST, and Chl-a anomaly

	Niño3.4	DMI	SST Anomaly	Chl-a Anomaly
Niño3.4	1.00			
DMI	0.38	1.00		
SST Anomaly	0.04	0.24	1.00	
Chl-a Anomaly	0.03	0.09	-0.02	1.00

CONCLUSION

This study found that extreme ENSO and IOD events occurring between November 2014 and April 2016 (El Niño) and between May 2019 and November 2019 (positive IOD) did not show a significant relationship with SST and Chl-a variations in Bone Bay, indicating that in semi-enclosed waters like Bone Bay, ENSO and IOD are not the primary factors driving SST and Chl-a dynamics. Local factors such as current dynamics, upwelling, and regional ocean-atmosphere interactions are likely to play a more significant role in determining oceanographic variability in this region. Therefore, further research is needed to explore these factors using numerical models and hydrodynamic simulations to gain a deeper understanding of the mechanisms contributing to SST and Chl-a changes. Additionally, these findings provide valuable insights for fisheries resource management in semi-enclosed waters, serving as a foundation for developing more adaptive regulatory policies for capture fisheries in response to environmental changes. Further studies with broader spatial and temporal coverage are highly recommended to ensure more effective adaptation strategies in addressing oceanographic variability and climate change impacts.

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