Changes in Pelagic Fisheries Composition in Relation to Climate Change: A Case Study of Prigi Waters, East Java

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Abstract

The variability of Sea Surface Temperature (SST) and chlorophyll-a distribution in the southern waters of East Java is heavily influenced by the Indian Ocean Dipole (IOD) phenomenon. This study examines oceanographic parameter variability, their relationship with the IOD from 2003 to 2014, and fishing dynamics in the southern waters of East Java, particularly at PPN Prigi. Data utilized include SST and chlorophyll-a from Aqua-MODIS satellites, the Dipole Mode Index (DMI), and 12 years of fish production records. The analysis reveals significant fluctuations in SST and chlorophyll-a, with a strong inverse relationship (correlation: −0.677), where chlorophyll-a concentrations rise as SST decreases. Positive IOD events reduce SST, while negative IOD events increase SST, with correlations of −0.591 for SST and IOD and 0.601 for chlorophyll-a and IOD. During the positive IOD events of 2006–2008, SST decreased, leading to increased fish production. Conversely, the negative IOD in 2010 raised SST, contributing to a decline in fish stocks. Over the 12-year period, a notable increase in Bali Sardinella and skipjack production was observed, despite a sharp decrease in 2010 caused by higher SST levels. This study highlights the importance of understanding the interactions between SST, chlorophyll-a, and IOD in developing sustainable fisheries management strategies. These insights can support efforts to optimize fish resource utilization, mitigate the impacts of climate variability, and ensure long-term fisheries productivity in the southern waters of East Java, particularly for strengthening adaptive resource planning within climate-sensitive pelagic ecosystems and supporting informed decision-making for regional fisheries policies and sustainable blue-growth initiatives.

Keywords: *Fish composition, Climate change, SST, Chlorophyll-a, IOD, South Prigi Waters*

Introduction

Prigi Waters, located in southern East Java, face the Indian Ocean and are significantly influenced by oceanographic phenomena such as the Indian Ocean Dipole (IOD) and seasonal upwelling (Fernanda *et al*., 2021). These factors crucially impact ocean productivity and nutrient availability, supporting small pelagic fish populations like Skipjack Tuna, Bali Sardinella, Indian Scad, and Mackerel. Studies show that climate phenomena, including the IOD and El Niño–Southern Oscillation, strongly affect variations in sea surface temperature, phytoplankton abundance, and fisheries (Subarna, 2018; Koesuma *et al*., 2021; Xu *et al*., 2021).

The IOD phenomenon significantly affects upwelling along Java's southern coast (Hatmaja *et al*., 2019), transporting nutrient-rich, colder subsurface water that enhances phytoplankton abundance, the primary food source for pelagic fishes (Safinatunnajah *et al*., 2021). Positive IOD events decrease sea surface temperatures and increase chlorophyll-a concentrations (Fernanda *et al*., 2021), promoting higher pelagic fish production (Ma'mun *et al*., 2018). In contrast, negative IOD events weaken upwelling, resulting in lower nutrient availability and reduced pelagic fish catch (Sartimbul *et al*., 2010). Understanding these interactions is crucial for developing sustainable fisheries management strategies in response to climate variability in Indonesian waters.

In addition to climate variability, global warming and changes in fishing pressure affect catch composition over time (Sartimbul *et al*., 2018; Kunarso *et al*., 2019; Safinatunnajah *et al*., 2021). Rising sea surface temperatures may force pelagic fish to migrate to cooler or deeper waters, impacting their spatial and temporal distribution (Tangke and Senen, 2020), while shifts in fish migration due to warming oceans directly influence fisheries productivity (Sumaila *et al*., 2011). High fishing pressure in the Prigi area has also led to changes in catch composition (Nikmah *et al*., 2019), and unchecked exploitation can result in overfishing and

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ecosystem imbalance (Kurohman *et al*., 2018). Seasonal patterns significantly affect catch dynamics, with peak landings occurring during the SE Monsoon and Inter-Monsoon II periods (Hendiarti *et al*., 2005; Setyohadi *et al*., 2021). The monsoon seasons include the SE Monsoon (June, July, August), Inter-Monsoon II (September, October, November), NW Monsoon (December, January, February), and Inter-Monsoon I (March, April, May) (Sartimbul *et al*., 2010; Wijaya *et al*., 2020; Sartimbul *et al*., 2023a).

The objectives of this study are to assess the variability of oceanographic parameters, analyse their relationship with the Indian Ocean Dipole (IOD) phenomenon from 2003 to 2014, and examine the dynamics of fishing in the southern waters of East Java, particularly at Prigi Nusantara Fishing Port, in relation to the IOD. Understanding changes in the composition of pelagic fish catches in Prigi is essential, as it depends on environmental factors and sustainable fisheries management practices that adapt to climate change. Researching oceanographic conditions during 2003-2014 is vital due to significant events like El Niño and La Niña, which affect Indonesia's oceanography. Notably, 2006 experienced lower sea surface temperature (SST) anomalies, while 2010 exhibited higher SST anomalies. Twelve years of data analysis reveals connections between global phenomena (El Niño-Southern Oscillation/ENSO) and regional phenomena (Indian Ocean Dipole/IOD), influencing climate change, droughts, and rainfall patterns. Further research can investigate recent trends, identify consistency in climate patterns, and develop effective adaptation strategies to forecast the impacts of climate change.

Materials and Methods

The research area is South Java Waters at 7°N to 14°N and 103°E to 115°E. This study focused on the fishing ground in the South Prigi waters, as shown in Figure 1. Due to the lack of environmental data at the fishing ground, satellite data was used. Monthly mean sea surface temperature (SST) data (2003-2014) derived from the Terra-Modis level 3 (version 4) satellite (Terra-Moderate-resolution Imaging Spectroradiometer) and chlorophyll-a data derived from the Aqua-Modis level 3 satellite were downloaded from the NASA Goddard Space Flight Center (GSFC) through the website http://oceancolor.gsfc.nasa.gov/cgi/. These data are 4 km pixel resolution products in HDF format.

The monthly mean Indian Ocean Dipole (IOD) index was utilized to investigate the potential relationship between climate variability and oceanographic data—specifically sea surface temperature and chlorophyll-a levels—and fish catch in the South Prigi waters. The IOD is a combined oceanic and atmospheric phenomenon occurring between the Indian Ocean and the equator (Saji *et al*., 1999), also referred to as the Indian Ocean Zonal (IOZ) mode (Webster *et al*., 1999). The positive phase of the IOD is characterized by an east-west dipole pattern in sea surface temperature (SST) anomalies across the Indian Ocean basin, spanning from Africa to Indonesia. A positive IOD phase typically leads to heavy rainfall in eastern Africa and drought conditions in Indonesia. Similar to the Pacific El Niño-Southern Oscillation (ENSO), the evolution of the IOD is closely linked to the annual cycle. In active years, cold SST anomalies near Java and Sumatra usually occur from June to August, peaking in September and October,

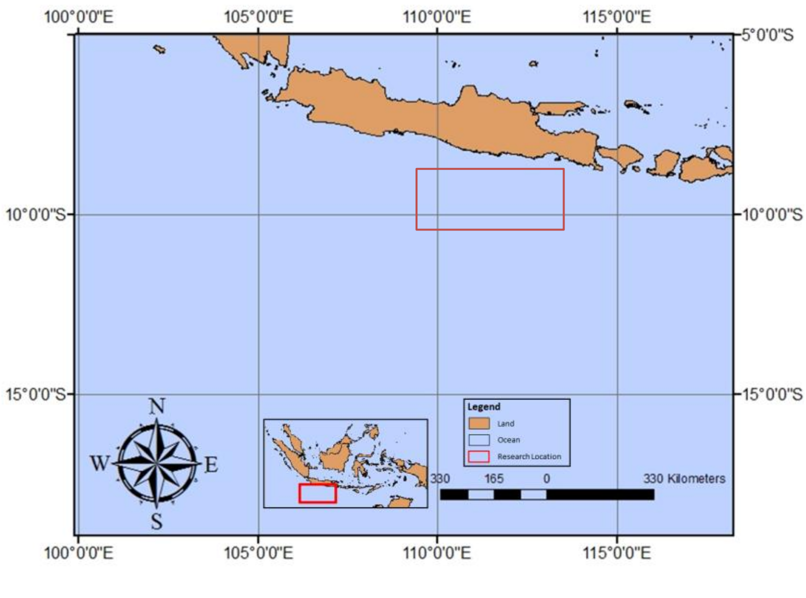

Figure 1. The study area (red square). Prigi Fishing Port is located in the south of East Java, Indonesia

while warm SST anomalies in the western Indian Ocean arise later (Qu *et al*., 2005). Sartimbul *et al*. (2018) explain that the anomaly method is an oceanographic analysis approach that measures the difference between observed values and long-term averages. This method, also used in meteorology and climate studies, has not been extensively detailed in previous research. IOD data were obtained from http://www.jamstec.go.jp/frsgc/research/d1/iod/jamstec.

Monthly average catches (2003–2014) were provided by the East Java Marine and Fisheries Service and Prigi Fishing Port (PPN Prigi-Indonesia). Catch per unit effort (CPUE) was used in this study to minimize problems in catch data collection and to standardize variations in fishing intensity over time. CPUE was calculated as the ratio between total catch (kg) and fishing effort, expressed as the number of fishing trips conducted per month, using the formula:

$$CPUE = \frac{Catch\ (kg)}{Fishing\ Effort\ (trips)}$$

Monthly SST, Chl-a, and CPUE averages in South Prigi water were plotted as a time series from 2003–2014. Furthermore, to evaluate anomalies in oceanographic parameters, the anomaly method was applied to detect conditions that deviate from long-term averages (Sartimbul *et al*., 2018). Anomalies were calculated using the formula:

$$Anomaly = Xi - X$$

where Xi represents the value of the parameter for month i, and X^{-} is the long-term oceanography monthly mean. This method indicates any deviation from normal conditions (Sartimbul *et al*., 2010). Correlations between SST and chlorophyll-a, and between chlorophyll-a and CPUE, were examined using Pearson's correlation coefficient. To understand the possible influence of climate variability on chlorophyll-a and CPUE south of Prigi waters, anomaly values were used to identify and highlight similarities and differences in environmental and fisheries responses across climate events.

Result and Discussion

Total fish catch

Based on fisheries statistics over a twelve-year period, the average catch landed at Prigi Fishing Port was 291,741,734 kg, with a maximum catch of 46,110,000 kg recorded in 2003 and a minimum of 5,505,286 kg in 2010 (Figure 2). The predominant species landed at PPN Prigi included Bali Sardinella (16.45%), Indian Scad (21.78%), Mackerel Tuna (27.67%), and Skipjack Tuna (2.74%). This data was then calculated into percentages to identify the dominant fish species constituting the total catch landed at Prigi Fishing Port each year.

Figure 3 illustrates the fluctuations in dominant fish catches at Prigi Fishing Port. In 2010, Tuna Mackerel comprised the highest percentage of total production at 62.52%, followed by Indian Scad in 2011 at 53.72%, and Bali Sardinella in 2008 at 35.33%. Prigi Waters, located in the southern part of East Java, are rich in large pelagic fish, particularly Tuna, Skipjack, and Mackerel (Hendrayana and Hartanti, 2018; Kurohman *et al*., 2018). The increase in Indian Scad catches in 2011 and the decline in Bali Sardinella in 2010 reflect shifts in fishing targets and habitats due to environmental changes (Yusuf and Hufiadi, 2020). Additionally, Figure 3 indicates a significant proportion of miscellaneous catches in 2003, comprised of non-dominant species, including jellyfish. Local fishermen captured large amounts of jellyfish to meet global market demand, exporting to China, Hong Kong, and Taiwan (Mochtar, 2004).

Biological aspects of pelagic fishes

Three group of fishes are discussed in this manuscript, i.e. small pelagic fishes (*Bali Sardinella* and *Indian Scad*), large pelagic fishes (*Mackerel Tuna* and *Skipjack Tuna*), and other fishes (Khaidar, 2015). Small pelagic fishes, measuring 10-30 cm, feed on plankton and small crustaceans and inhabit shallow waters at depths of 15-100 m, with a sea surface temperature (SST) tolerance of 26-29°C (Rahadian *et al*., 2019). In contrast, larger pelagic fishes range from 50-100 cm, feed on smaller fish and squid, inhabit deeper waters, and tolerate SSTs between 15-25°C (Ramadhanty *et al*., 2021). The dynamics of these fish and their food sources are influenced by environmental factors such as SST and climate variability, including the Indian Ocean Dipole (IOD). A positive IOD boosts phytoplankton and zooplankton production, enhancing the growth of small pelagic fish and subsequently supporting large pelagic fish production in the following months due to the time lag in the grazing process (Sartimbul *et al*., 2010; 2023a). Vice versa for negative IOD (Pratiwi *et al*., 2023). Fish adaptation to SST changes includes vertical and horizontal migration, changes in foraging activities, and reproduction (Ramadhanty et al., 2021).

Variability of SST and Chl-a concentration

The variability of sea surface temperature (SST) and chlorophyll-a concentrations in the waters of Southern Java is closely interconnected. From

2003 to 2014, the average chlorophyll-a content exhibited significant seasonal variation, peaking at 0.31 mg.m^{-3} in August (Figure 5). Chlorophyll-a concentrations increase during the first transition season, reaching their highest levels in the Southeast monsoon months (June, July, August) before declining in the second transition season (Sartimbul *et al*., 2010; Piontkovski *et al*., 2011; Auliati *et al*., 2021). This variation is driven by SST fluctuations, as higher chlorophyll-a levels indicate increased nutrient availability from cool deep water during upwelling events (Sartimbul *et al*., 2010; Wulandari *et al*., 2018). Additionally, water mass movements and phenomena such as the Indian Ocean Dipole (IOD) contribute to these dynamics and extend the duration of the upwelling process, as observed in 2019 (Sartimbul *et al*., 2021).

The relationship between chlorophyll-a and sea surface temperature (SST) is further illustrated by the seasonal SST variation in Southern Java waters (Figure 6), which aligns with general SST fluctuations (Figure 4). Indonesia experiences four distinct seasons: the Northwest (NW) Monsoon (December-February), the first inter-monsoon (March-May), the Southeast Monsoon (June-August), and the second inter-monsoon (September-November). The highest average SST occurs in March at 29.83°C, while the lowest mean temperature is recorded in August and September at 26.30°C (Figure 5).

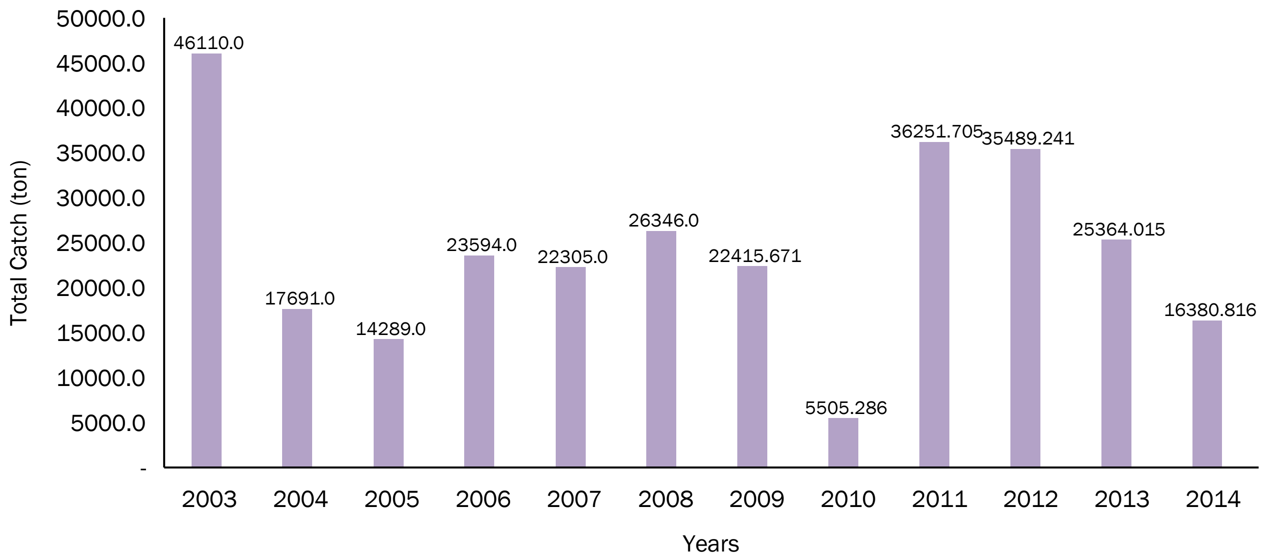

Figure 2. Total Fish catch landed at Prigi Port for twelve years (2003-2014)

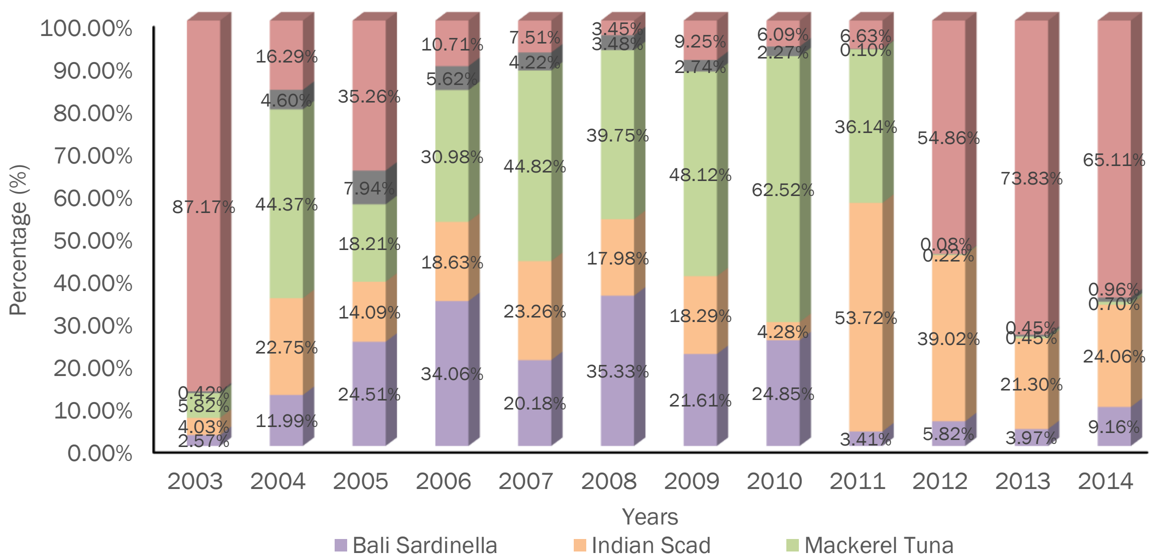

Figure 3. Percentage of dominant fish caught landed at Prigi Fishing Port each year

SST patterns are significantly influenced by monsoon wind patterns. During the Southeast Monsoon (June, July, August), winds from high-pressure areas in winter Australia blow towards low-pressure summer Eurasia, causing surface water to move away from the South Coast of Java, including Prigi Waters. This movement creates a vacuum at the surface, allowing cool, nutrient-rich deep water to rise in a process known as upwelling. Conversely, during the Northwest Monsoon (December, January, February), the absence of winds from summer Australia keeps SST high, resulting in lower chlorophyll-a concentrations (Sartimbul *et al*., 2010; Yulianto *et al*., 2018; Muhammad *et al*., 2021; Sartimbul *et al*., 2023a).

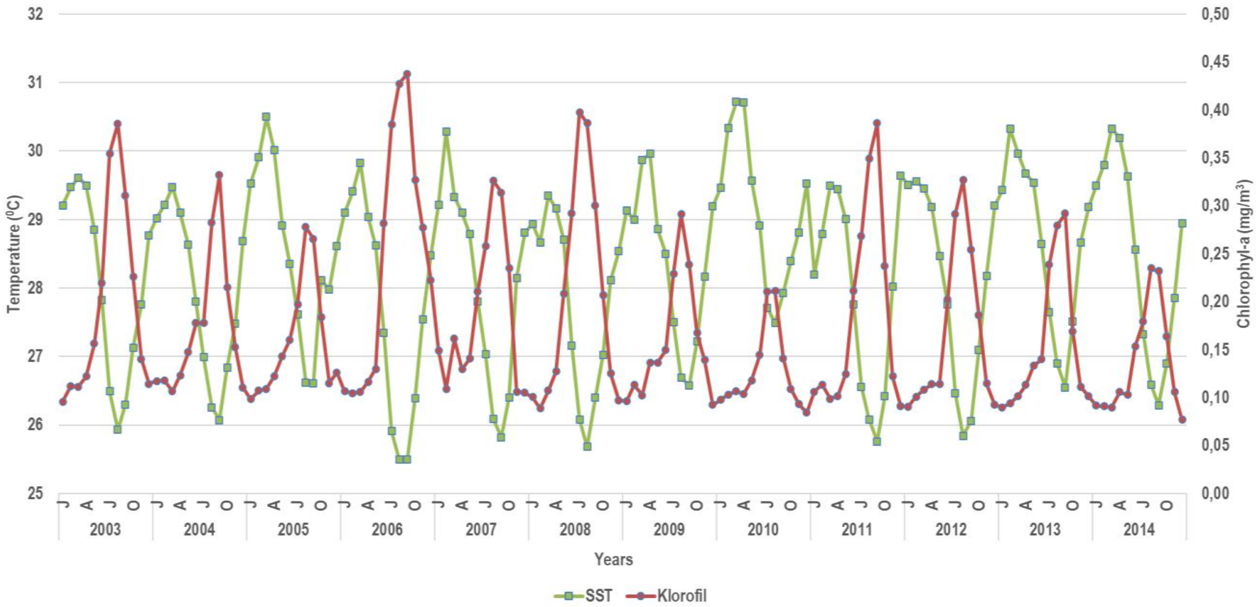

Figure 4. Time series of monthly mean sea surface temperature and chlorophyll-a concentration (2003–2014)

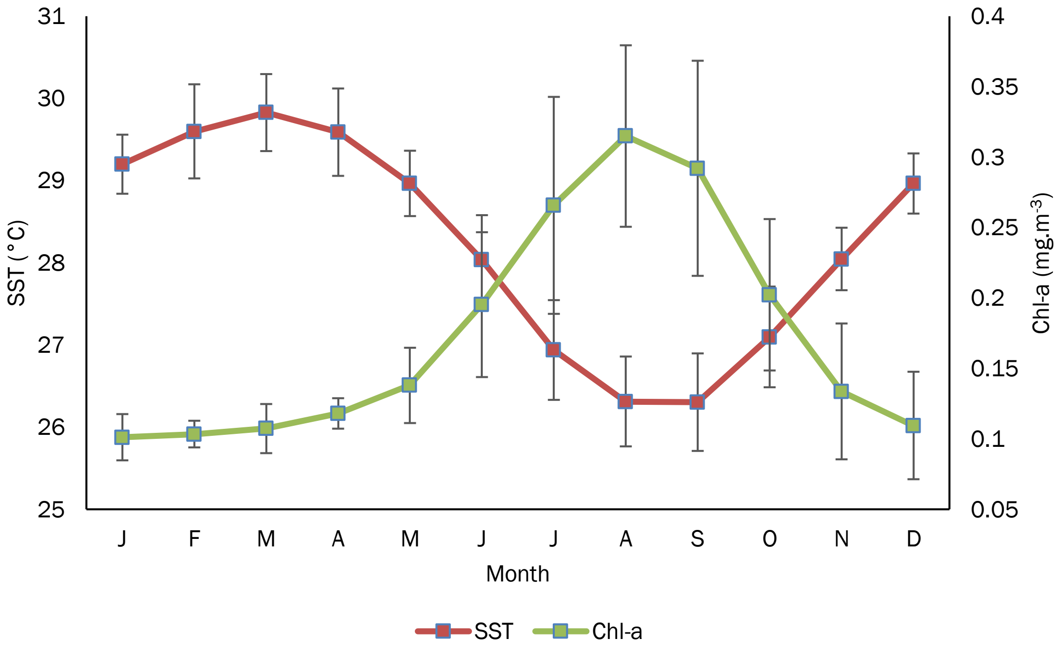

Figure 5. Seasonal variation of sea surface temperature and Chlorophyll-a concentration in Prigi Waters. Its seasonal variation follows a monsoonal pattern, SE Monsoon (June–August), Inter-Monsoon II (September–November), NW Monsoon (December–February), Inter-Monsoon I (March–May).

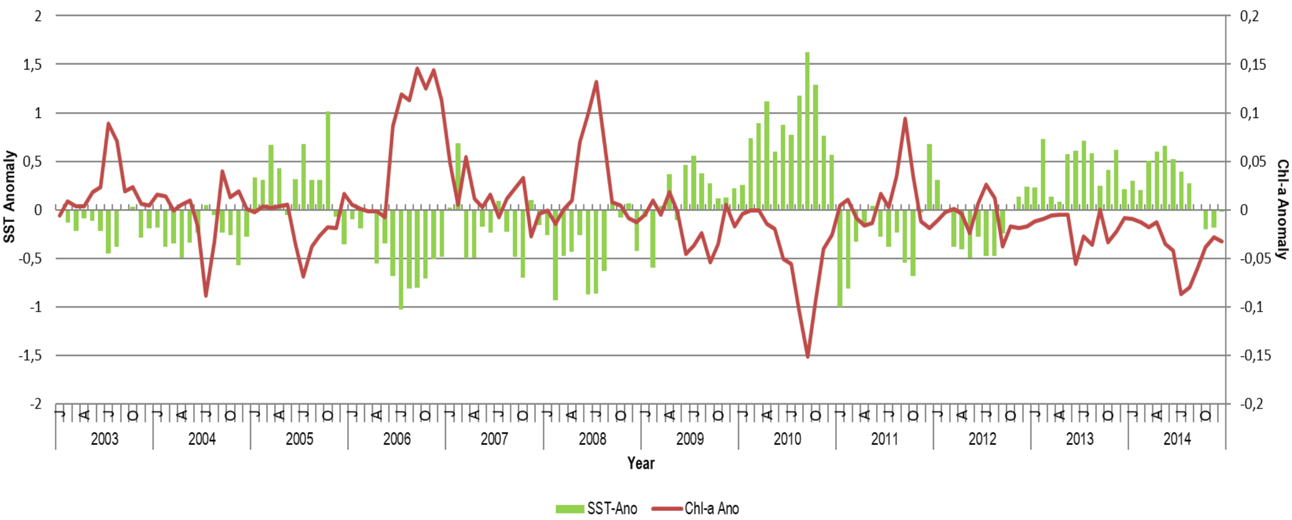

Figure 6. Chlorophyll-a and Sea Surface Temperature anomaly at Prigi waters (2003–2014). Decreased Sea Surface Temperature due to strong anomalous south easterly winds during El Niño and Indian Ocean Dipole events in 2006 generated anomalous upwelling and produced high chlorophyll-a.

Figure 6 illustrates the twelve-year dynamics of sea surface temperature (SST) and chlorophyll-a in Prigi Waters. A common pattern emerges low temperatures indicate upwelling, which is followed by an increase in chlorophyll-a concentration (Yulianto *et al*., 2018; Muhammad *et al*., 2021). Conversely, high temperatures indicate a lack of upwelling, resulting in decreased chlorophyll-a levels. Notably, a significant anomaly occurred in 2006, when prolonged upwelling was associated with the highest chlorophyll-a concentration anomaly observed during the study period (Fernanda *et al*., 2021; Maslukah *et al*., 2014).

IOD (Indian Ocean Dipole)

The Indian Ocean Dipole (IOD) is a phenomenon like El Niño, occurring in the Indian Ocean and exemplifying the interaction between tropical air and sea. A positive IOD is marked by warmer sea surface temperatures (SST) in Africa and cooler SST in southern Indonesia, resulting from weakened westerly winds, and vice versa (Saji *et al*., 1999; Webster *et al*., 1999; Ramadhanty *et al*., 2021). Like the Pacific ENSO, the IOD's development is closely linked to the annual cycle. During active years, cold SST anomalies off the coasts of Java and Sumatra typically occur between June and August, peaking from September to October, while warm SST anomalies in the western Indian Ocean appear later (Qu *et al*., 2005; Sartimbul *et al*., 2018). The IOD has a more significant impact on the oceanography of western Sumatra, southern Java, Bali, and Timor, especially when influenced by El Niño events. The interaction between the IOD and ENSO affects chlorophyll-a concentrations and fish catches, as observed in pelagic fisheries in the Bali Strait in 2006 (Sartimbul *et al*., 2010) and Prigi Waters (Khaidar, 2015; Sartimbul *et al*., 2018). When the IOD is in a positive phase, strengthened by El Niño, it intensifies upwelling, leading to lower SSTs and increased chlorophyll-a levels, which, in turn, result in higher fish catches.

Relationship among variables: SST, chlorophyll-a, fishes catch, and IOD

Figure 7 illustrates the time series dynamics of all parameters (SST, chlorophyll-a, catch, and IOD index) over twelve years in Prigi Waters. A significant drop in sea surface temperature (SST) was observed in 2006, while a rise occurred in 2010, corresponding to climatic events associated with positive and negative IOD phases, respectively. In 2006, the IOD was positive, indicating strong upwelling in southern Indonesian waters, particularly in Prigi. This resulted in SSTs decreasing by 1°C below the twelve-year average and an increase in chlorophyll-a concentrations, leading to a rise in catches of Bali sardine (about 200,000 kg), Mackerel tuna (300,000 kg), and Skipjack tuna (30,000 kg) above their twelve-year averages. This aligns with findings from Sartimbul *et al*. (2010). Conversely, in 2010, during a negative IOD phase, SSTs rose by 1.63°C above the twelve-year average due to a lack of upwelling, which caused a drop in chlorophyll-a (0.15 mg/m^3) and nearly zero fish catches in Prigi Waters. These results are consistent with studies by Khaidar (2015) and Sartimbul *et al*. (2018). The absence of these species altered the catch composition in Prigi Waters, similar to findings by Sartimbul *et al*. (2018) in the Bali Strait.

The complex and dynamic relationships among sea surface temperature, primary productivity, fish catch, and climate variation are highlighted in Figure 7. The inverse relationship between SST and chlorophyll-a concentration emphasizes the crucial role of upwelling in supplying nutrients for phytoplankton growth (Ma'mun *et al*., 2018). An increase in chlorophyll-a, as the base of the food chain, directly supports higher fish production (Agung *et al*., 2018). Climatic phenomena such as IOD also have a significant influence on the dynamics of these ecosystems. Ongoing climate change may reinforce existing patterns and trigger more dramatic changes in marine ecosystems (Nugroho, 2019).

The analysis related to Figure 5 reveals the seasonal variation of sea surface temperature (SST) and chlorophyll-a concentrations. While long-term variations align with Figure 5, they are more complex due to climatic changes as elaborated in Figure 7. Higher chlorophyll-a concentrations often result from upwelling events, characterized by lower SST. This phenomenon occurs when cold, nutrient-rich water from the ocean floor rises to the surface, supplying phytoplankton with essential nutrients (Uneputty *et al*., 2022). The abundant nutrients promote rapid phytoplankton growth, leading to increased chlorophyll-a concentrations (Rosdiana *et al*., 2017). Conversely, during periods of elevated SST without upwelling, chlorophyll-a concentrations tend to decrease. Warm water, being less dense, inhibits vertical mixing, which traps nutrients in deeper layers and prevents them from reaching the surface. This limitation hampers phytoplankton growth, resulting in reduced chlorophyll-a levels (Muhammad *et al*., 2021). However, the relationship is not always straightforward; factors such as ocean currents, wind conditions, and light availability also influence chlorophyll-a distribution and SST. For instance, global climate change can alter upwelling patterns and increase SST, thereby affecting ocean productivity dynamics (Gao *et al*., 2013; Shi *et al*., 2023).

In general, chlorophyll-a concentration variability in the waters of southern Indonesia, including Prigi Water and the Bali Strait, follows a monsoonal pattern: SE Monsoon, Inter-Monsoon II, NW Monsoon, and Inter-Monsoon I. The southeast monsoon is characterized by elevated chlorophyll-a levels, as southeast winds from Australia push warm surface water away from the coast, facilitating upwelling. This process brings cooler, nutrient-rich waters to the surface along the southern coasts of Java, Bali, Timor, and nearby seas. In contrast, the northwest monsoon creates opposite conditions (Sartimbul *et al*., 2010; 2023a; 2023b).

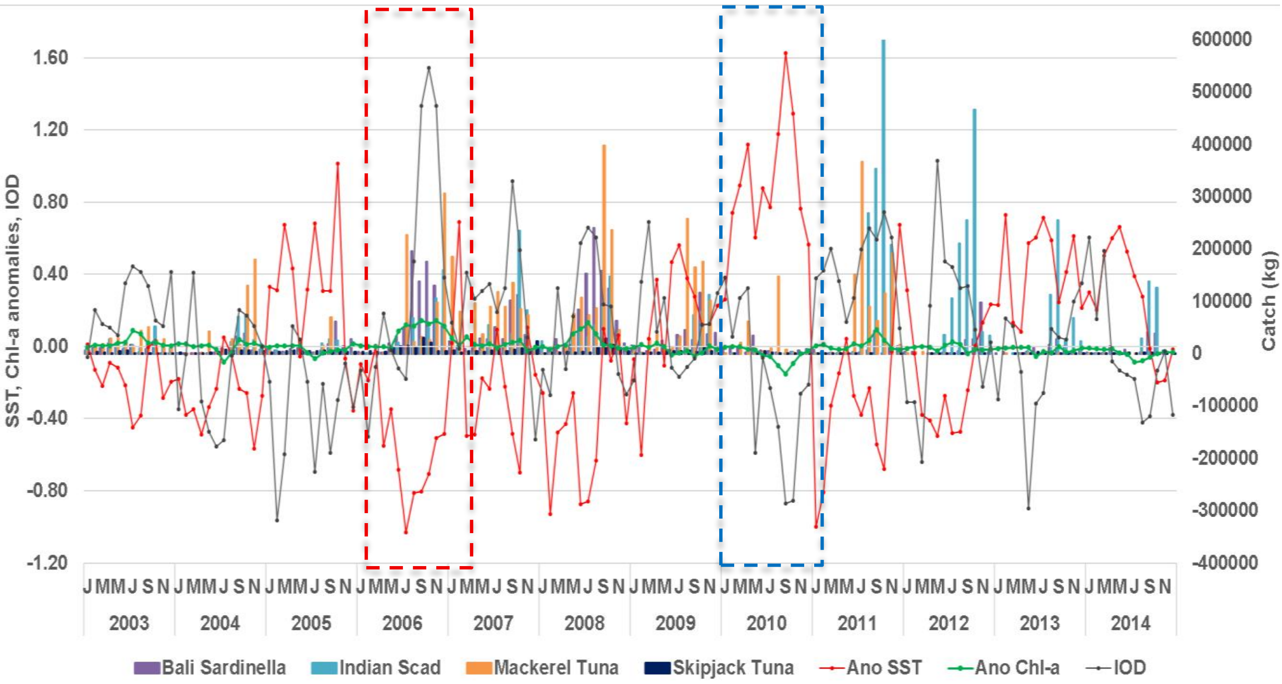

Figure 7. Time series of SST, Chlorophyll-a, IOD, and catch of fishes (Bali Sardine, Indian Scad, Mackerel Tuna, and Skipjack Tuna). Red (blue) dash line indicated IOD+ (IOD-)

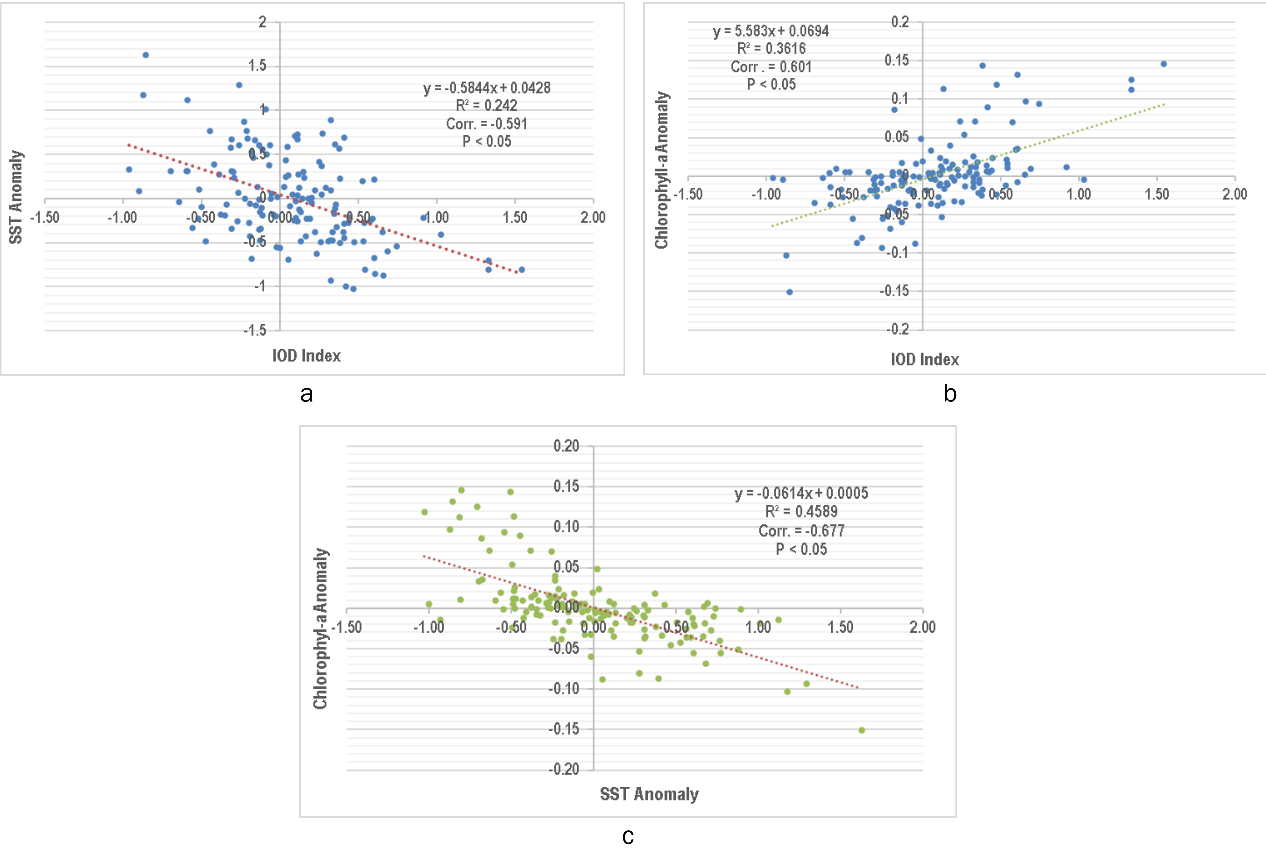

Figure 8. a) Correlation between IOD and SST; b) Correlation between IOD and Chl-a; and c) Correlation between Chl-a and SST

Climate index correlation

Statistical analysis using the Pearson correlation method was conducted to examine the relationships between the Indian Ocean Dipole (IOD) and sea surface temperature (SST), IOD and chlorophyll-a, and SST and chlorophyll-a. The results indicate a negative correlation between IOD and SST (R= -0.591) (Figure 10a), implying that an increase in the IOD index corresponds with a decrease in SST, and vice versa. Conversely, there is a positive correlation between the IOD index and chlorophyll-a (R= 0.61), suggesting that an increase in the IOD index is associated with higher chlorophyll-a levels. Additionally, a negative correlation exists between SST and chlorophyll-a (R= -0.677) (Figure 10c), indicating that an increase in SST leads to a decrease in chlorophyll-a, and vice versa. These findings align with previous studies by Sudradjat *et al*. (2024) and Sartimbul *et al*. (2010). Beyond seasonal variations, climatic factors such as the IOD directly influence and extend seasonal variations in SST and chlorophyll-a, with subsequent effects on fish populations. Positive or negative IOD phases, along with increasing or decreasing westerly winds and upwelling intensity, support fisheries in the region (Iskandar *et al*., 2017; Sartimbul *et al*., 2018).

Figure 10 also presents a regression analysis that quantifies the relationships between parameter changes. The coefficient of determination, R^2= 0.4589 (significant at P< 0.05), indicates that changes in sea surface temperature (SST) significantly influence changes in chlorophyll-a concentration (Figure 10c). Specifically, 45.9% of the variation in chlorophyll-a concentration is attributed to changes in SST, while 54.1% is attributed to other factors. Similarly, changes in the Indian Ocean Dipole (IOD) affect SST and chlorophyll-a, with coefficients of determination of R^2= 0.2414 and R^2= 0.3616, respectively (Figure 10a and b). These findings highlight the importance of incorporating environmental and climate variables into fishing forecasts, particularly in an increasingly unpredictable climate. Long-term studies with reliable fishing data are expected to enhance understanding of fishing zones and reduce losses in future fishing activities.

Conclusion

This study demonstrates the critical impact of the Indian Ocean Dipole (IOD) on the variability of Sea Surface Temperature (SST) and chlorophyll-a distribution in the southern waters of East Java. The identified relationships between oceanographic parameters and fishing dynamics reveal that fluctuations in SST and chlorophyll-a are closely linked to IOD events, influencing fish production trends significantly. The findings indicate that positive IOD phases lead to favorable conditions for fish stocks, while negative IOD events can adversely affect fisheries. Notably, the increase in Bali Sardinella and skipjack production over the examined decade underscores the need for proactive fishery management strategies that account for environmental variability. By understanding these interactions, stakeholders can enhance resource utilization, reduce the effects of climate variability, and promote sustainable fishing practices. Ultimately, this research provides valuable insights into regional fisheries policies aimed at ensuring the long-term productivity of pelagic ecosystems and supporting sustainable blue-growth initiatives in the face of climate change.

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