



# Relationship Between Seasonal Oceanographic Parameter Fluctuations and Migration of Spanish Mackerel in Bengkulu Waters, 2013–2023

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Mackerel fish are a high-value fishery commodity whose migration patterns are influenced by several oceanographic factors. This study aimed to identify the influence of seasonal fluctuations in oceanographic parameters on the migration of tenggiri fish during 2013-2023 in seven waters of Bengkulu. Oceanographic data were obtained from the Marine Copernicus. The data were obtained from the Multi-Observation Global Ocean 3D Temperature Salinity Height Geostrophic Current and MLD product for the period from 2013 to 2023, with a spatial resolution of 0.125°, while the catch data were obtained from the Bengkulu Province Marine and Fisheries Department. The data were processed spatially and temporally using GrADS, Panoply, and ArcGIS. The results of the study show that temperature, salinity, and currents tend to be stable throughout the year, whereas chlorophyll-a and wind experience significant seasonal fluctuations. In Kaur, Bengkulu City, and North Bengkulu regions, spikes in chlorophyll-a and wind intensity during the Australian Monsoon and Transition II were positively correlated with increased mackerel catch yields. Conversely, areas such as Seluma and Central Bengkulu did not show a clear relationship between oceanographic parameters and catch yield. These findings confirm that chlorophyll-a and wind play a greater role in mackerel migration than do temperature or salinity.

**Keywords:** Mackerel fish; Oceanographic parameters; Fish migration; Bengkulu waters

## 1. Introduction

Mackerel (*Scomberomorus commerson*) is one of the pelagic fishery commodities that has high economic value and is widely distributed in tropical and subtropical waters, including in Indonesian waters. As an active predator, this fish exhibits complex migration patterns influenced by various oceanographic factors such as sea surface temperature (SST), chlorophyll-a concentration, salinity, and ocean currents. Understanding the migration patterns of Spanish mackerel is crucial for supporting sustainable fishery management.

The waters of Bengkulu, located along the west coast of Sumatra, are potential areas for mackerel fishing. One of the challenges in

fisheries management is the reliance on traditional fishermen's knowledge to determine fishing areas. However, this knowledge is often insufficiently responsive to dynamic environmental changes. Therefore, the use of remote sensing technology and oceanographic data is crucial to scientifically complement the spatial and temporal distribution of fish resources. Such studies can improve the effectiveness and efficiency of fishing activities by identifying potential fish locations based on oceanographic indicators, such as SST, chlorophyll-a, and ocean currents.

Previous research has shown that the sea surface temperature and chlorophyll-a

concentration are correlated with the presence of pelagic fish. For example, a study of Bali waters showed that increases in sea surface temperature and chlorophyll-a concentration were correlated with increased mackerel catches from August to December [1].

In addition, the variability of oceanographic parameters has been studied in other regions of Indonesia. Research in the waters of North Sulawesi revealed that sea surface temperature, chlorophyll-a, and surface wind exhibit spatially and seasonally variable patterns, that influence the distribution of marine organisms [2]. Studies in the Sulawesi Sea also show that the distribution of fish larvae is related to oceanographic conditions such as temperature and salinity, which influence their abundance and spatial distribution of fish larvae [3].

In the waters of the Sunda Strait, analysis of the relationship between seasonal oceanographic conditions and pelagic fish catches shows that fluctuations in sea surface temperature, chlorophyll-a concentration, current patterns, and salinity affect fish catches [1]. Similarly, a study in the Bali Strait found that seasonal fluctuations in sea surface temperature and chlorophyll-a concentration were correlated with skipjack tuna catches, which are pelagic fish such as mackerel [1].

Research in the Java Sea shows that variations in oceanographic parameters, such as temperature and salinity, are influenced by monsoon winds and the global ENSO climate, which in turn affects fish distribution [4]. Studies in the waters of Palabuhanratu also revealed that the fishing season for pelagic fish, such as mackerel, generally occurs during the East Monsoon season, with a close relationship between fish production and monthly fluctuations in sea surface temperature and chlorophyll-a concentration [5].

This study only discusses in general terms the influence of oceanographic parameters such as wind speed, ocean currents, salinity, sea surface temperature, and chlorophyll-a concentration on the catch of mackerel (*Scomberomorus* spp.). This study does not specifically address the influence of large-scale oceanographic phenomena such as the El Niño

Southern Oscillation (ENSO), La Niña, Indian Ocean Dipole (IOD), or other climate phenomena. The focus of this study is limited to the relationship between basic oceanographic parameters and mackerel catch yields during the specified period and in the designated region. Although various studies have been conducted in different Indonesian waters, research specifically examining the relationship between seasonal oceanographic parameter variability and mackerel migration patterns in Bengkulu remains limited. Therefore, this study aimed to identify the influence of seasonal oceanographic parameter fluctuations on mackerel migration during the 2013-2023 period in seven Bengkulu waters. This study also focused on determining the oceanographic parameters that play the most significant role in shaping the habitat preferences of mackerel. The results of this study are expected to provide useful information for sustainable fisheries management and improve the efficiency of mackerel fishing in Bengkulu.

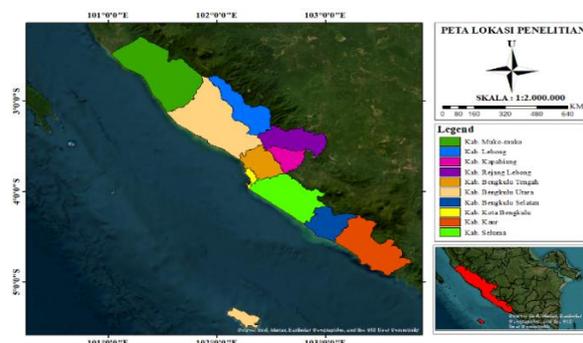


Figure 1. Map of Research Location

## 2. Materials and Methods

### 2.1 Location and Time of Research

The research location is in the waters of Bengkulu, which directly faces the Indian Ocean, and is geographically located at coordinates 3°-5°LS and 101°-104°BT. This study was conducted between August and December of 2023.

### 2.2 Materials and Tools

This study uses oceanographic data in the form of sea surface temperature, salinity of Bengkulu waters, wind speed and direction, and sea current speed and direction in Bengkulu

waters. The data were obtained from the Multi-Observation Global Ocean 3D Temperature Salinity Height Geostrophic Current and MLD product for the period from 2013 to 2023, with a spatial resolution of 0.125°, available on the Marine Copernicus website. The data used were near real-time monthly and reprocessed monthly, consisting of monthly data over a 10-year period, covering 50 depth levels from the surface to the seabed. The parameters extracted included geostrophic eastward sea water velocity ( $u_{go}$ ), geostrophic northward sea water velocity ( $v_{go}$ ), sea water salinity ( $so$ ) in units of 0.001, chlorophyll-a, and sea water temperature ( $to$ ). Additionally, data on mackerel catches from the Marine and Fisheries Department (DKP) of Bengkulu Province during the same period, from 2013 to 2023, was also utilized. The equipment used for data processing included a laptop or computer as well as software such as Excel, GrADS, and Panoply.

### 2.3. Data Processing Techniques

Patterns of the distribution of current speed, wind speed, sea surface temperature, chlorophyll-a, and salinity were analyzed based on satellite image data. The wind speed, sea surface temperature, and salinity data obtained are still global; therefore, a more specific data extraction process is needed according to the study area using a data pick program. After the data were focused on Bengkulu waters, they were processed using GrADS software. In this process, the data were first selected and sorted based on seasonal variations, namely the west, transition I, east, and transition II seasons, to facilitate spatial-temporal analysis.

Furthermore, the visualization results from the GrADS were exported and further processed using Panoply software to obtain the average value of each oceanographic parameter that had been mapped. The average values were compiled and processed using Microsoft Excel to facilitate the statistical calculations and graphical preparation. The processed data was then compared and correlated with fish catch data obtained from the Bengkulu Province Marine and Fisheries Service (DKP), in order to determine the relationship between

oceanographic parameters and seasonal mackerel catch distribution patterns.

Descriptive and quantitative analysis methods were used in this. Quantitative analysis in this study was conducted to understand the relationship between fluctuations in oceanographic parameters and mackerel (*Scomberomorus* spp.) catch yields based on numerical and spatial-temporal approaches. This analysis includes observations of oceanographic parameter values such as sea surface temperature (SST), ocean current velocity, salinity, chlorophyll-a, and wind speed, obtained from satellite imagery between 2014 and 2023. Fish catch data were obtained from the Marine and Fisheries Service and processed in tons based on season. The relationships between variables were analyzed quantitatively through numerical trend observations and descriptive spatial correlations, matching the location and timing of oceanographic parameter changes with the distribution patterns of fish catches. Each parameter was analyzed in the form of seasonal time series to observe the movement of values from year to year and between seasons (West Season, Transition I, East Season, and Transition II). These data were then analyzed in relation to fluctuations in fish catches to understand the influence of oceanographic factors on migration patterns and seasonal concentrations of mackerel in Bengkulu waters.

## 3. Results and Discussion

### 3.1 Spatial and Temporal Relationship between Winds with Ocean Currents

The visualization results in Figure 2 show the spatial relationship between wind and ocean currents based on season. In this visualization, arrows represent the direction and strength of ocean currents, while colors represent the intensity of surface winds. During the West Season (a), the currents are scattered and irregular but tend to flow from southwest to northeast. There are eddies in the southeast that indicate local dynamics [6]. The color scale shows that the current speed varies from <0.5 m/s (blue–purple) to >4 m/s (pink). The dominant wind direction from the west causes

surface currents to flow eastward, in line with the wind. Upon entering Transition Season I (b), the current is still predominantly from the southwest to the northeast. Current eddies appear in the central and southern regions,

while along the coast, the current follows the coastline. The highest current speed reaches  $>1.2$  m/s (red), and the current becomes more unstable due to weakening winds and changing directions.

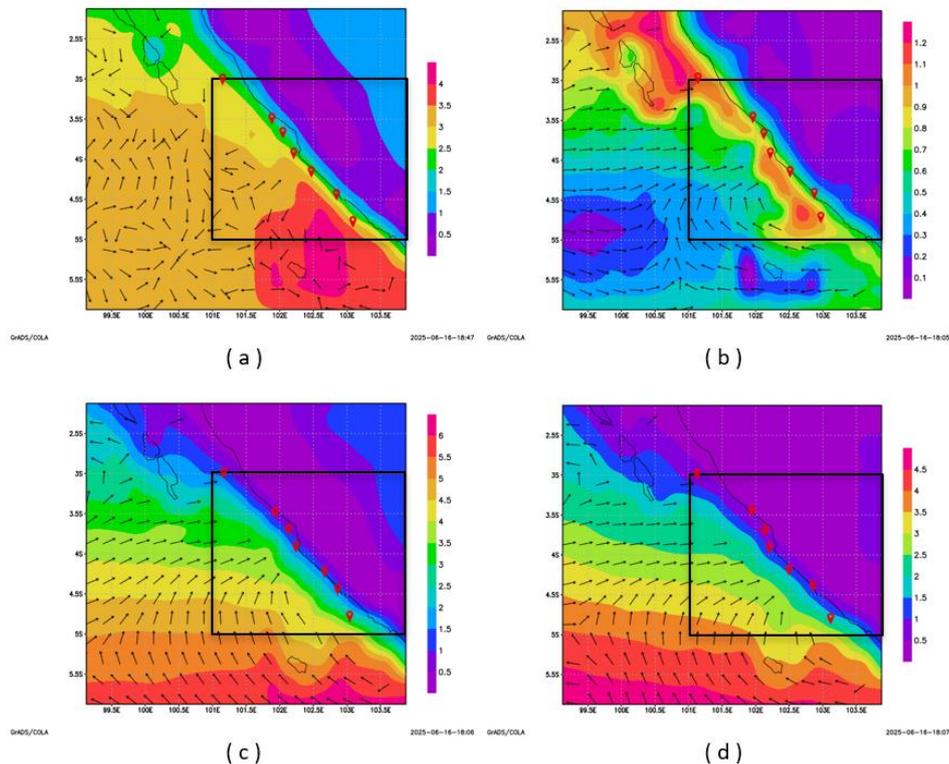


Figure 2. Relationship between wind and ocean current based on seasonal variations from 2013-2023: a) West Season, b) Transition Season I, c) East Season, d) Transition Season II

During the East Season (c), the current flows steadily from southwest to northeast, especially in the open sea. Near the coast, the current runs parallel to the coastline and tends to be stable and linear. The highest current speed is  $>5$  m/s (pink), especially in the south. Strong southeasterly winds push strong currents toward the northwest and trigger upwelling processes. Meanwhile, green, blue, and purple indicate weak to very weak currents ( $<2$  m/s). Furthermore, the Second Transition Season (d) the movement is dominated by a southwest to northeast flow pattern, which tends to be linear and follows the coastal contours in coastal areas. The color scale depicts the gradation of current velocity, with the highest values ( $>4$  m/s) in the southern part (red) and the lowest values ( $<1$  m/s) around the northeast coast (purple), as shown in Figure 2.

These findings are consistent with those of previous studies, which show that seasonal monsoon winds play an important role in controlling ocean current variability in the Indonesian region [7]. A previous study [7] covering the period from 1950 to 2013 in the waters of the South China Sea showed differences from the results of this study for the period from 2013 to 2023. These differences are evident in small shifts in wind direction and intensity, which impact changes in surface ocean current patterns [8]. This shift is thought to be related to the increased frequency of extreme climate events, such as El Niño and the impact of global climate change [9]. Previous research also supports this finding, stating that global warming causes changes in regional wind patterns that impact the ocean circulation systems in tropical regions [10].

### 3.2 Spatial and Temporal Relationship between Salinity with Ocean Currents

The visualization results in Figure 3 show that the salinity and current direction undergo significant changes between seasons. During the Asian Monsoon (a), the salinity distribution appears uneven, with a predominance of blue-purple colors indicating low salinity

(approximately 30–32 PSU), accompanied by random current patterns. This indicates the influence of high rainfall and freshwater input from the land [11]. During Transition Season I (b), there was an increase in salinity (32–34 PSU), particularly in the central and western parts of the study area. Currents begin to flow in a relatively uniform direction, indicating a transition in wind dynamics [11].

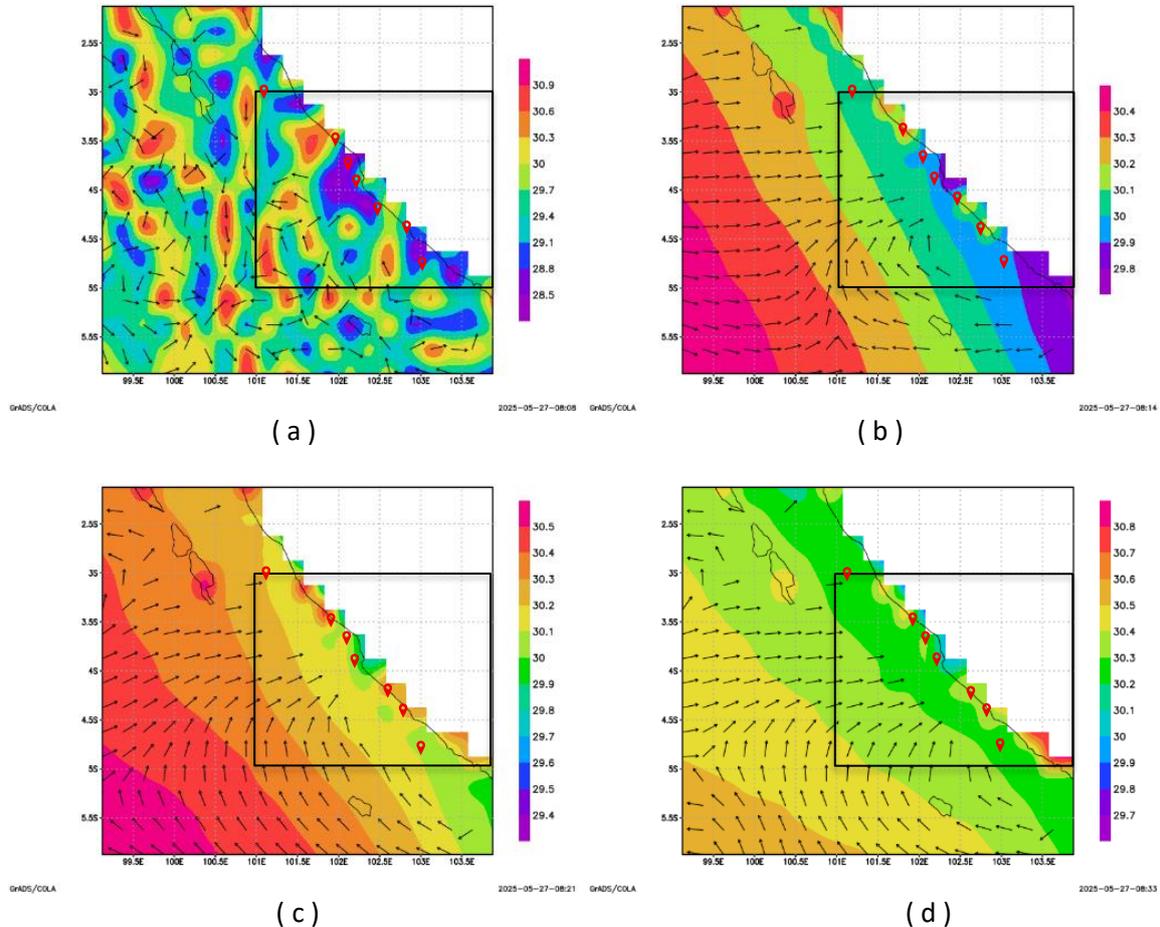


Figure 3. The relationship between salinity (color gradient) and ocean current (arrow direction) and ocean currents based on seasonal variations from 2013-2023: a) West Season, b) Transition Season I, (c) East Season, d) Transition Season II.

Meanwhile, the Australian Monsoon (c) shows the highest salinity values (red-orange, >34.5 PSU), with dominant current directions from southeast to northwest [11]. This phenomenon is closely related to upwelling events that bring saltier deep seawater to the surface. Conversely, in the Second Transition Season (d), salinity slightly decreased (32-34 PSU), and the current direction became unstable again, indicating a transition toward the West Season [11]. During the West Season (Figure 3a),

minimum salinity values were identified in the Seluma region, ranging from 29.1 to 29.4 PSU. The maximum salinity values were recorded during the Second Transition Season (Figure 3b) in the Seluma and South Bengkulu regions, ranging from 30.2 to 30.3 PSU.

Seasonal circulation and physical oceanographic processes such as upwelling and rainfall significantly influence salinity and ocean currents [11]. This indicates that salinity variation plays a crucial role in seasonal

oceanographic changes. This finding supports previous research in the South China Sea showing how seasonal current changes affect pelagic fish distribution [12]. However, unlike other studies that recorded weak current patterns during the transition season, these results show a clear current pattern during Transition Season II, which may have been influenced by local conditions or annual variations [13].

### 3.3 Spatial and Temporal Relationship between

### Temperature with Ocean Currents

According to the results shown in Figure 4, seasonal changes associated with monsoon winds greatly affect the sea surface temperatures and current patterns in the study area. During the Asian monsoon season (a), sea temperatures are warmer because westerly winds carry warm water masses from the Indian Ocean, causing currents to become dynamic and irregular [14].

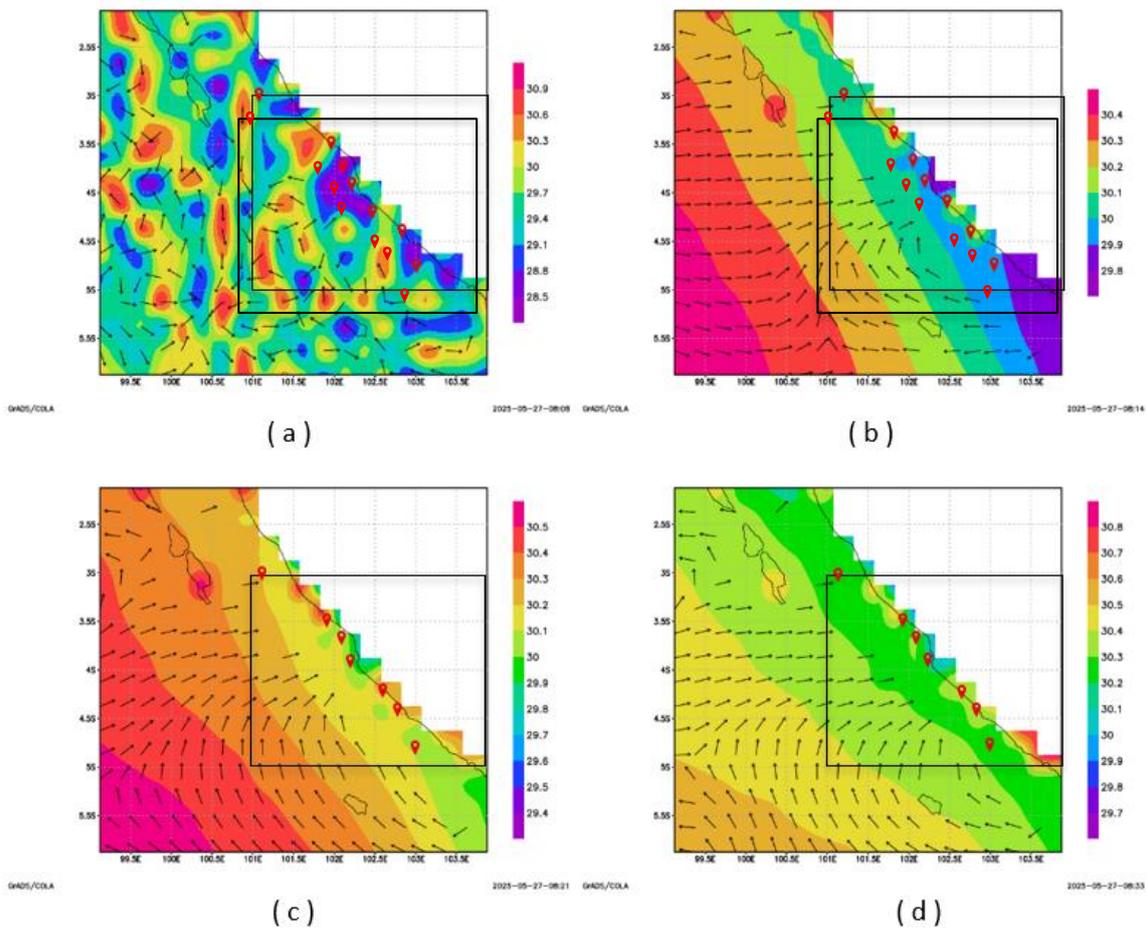


Figure 4. Relationship between temperature (color gradient) and ocean current (arrow direction) based on seasonal variations 2013-2023: a) West Season, b) Transition Season I, c) East Season, d) Transition Season II

Conversely, during the Australian Monsoon (c), sea surface temperatures are cooler, with strong directional currents flowing from east to northwest. This occurs because of upwelling, the process of cold, nutrient-rich deep seawater rising to the surface, driven by the eastern monsoon winds. This upwelling is crucial for marine

productivity and stabilization of current patterns [14]. During Transition Seasons I (b) and II (d), temperature and currents exhibit transitional patterns between the wet and dry seasons. The direction and strength of the currents change in response to shifts in monsoon winds, indicating that the marine system adapts to seasonal changes.

This pattern illustrates how marine conditions dynamically change with seasons, which is important for understanding marine environmental variability [15]. During the west monsoon season (Figure 4a), the maximum sea surface temperature was observed in the Seluma region, ranging from 29.7 to 30°C. Conversely, during transition season II (Figure 4b), the minimum

### 3.4 Spatial and Temporal Relationship between Chlorophyll-A With Ocean Currents

Figure 5 shows the relationship between the chlorophyll-a concentration and ocean currents based on seasonal variations from 2013 to 2023. During the Asian Monsoon (a) and Transition I (b), chlorophyll-a concentrations were relatively low and confined to coastal areas, indicating minimal biological activity in the open waters. Conversely, during the Australian Monsoon (c) and Transition II (d), increases in chlorophyll-a concentrations were primarily observed along the coastline and in areas affected by upwelling currents. The

temperature was recorded in the Central Bengkulu region, reaching 25.2°C.

Overall, these findings are consistent with the understanding that seasonal circulation and physical processes, such as upwelling, greatly influence sea temperature and currents, which ultimately impact coastal ecosystems and environments [14].

dominant westward and southward ocean currents during this season contributed to the upwelling of nutrients from the lower ocean layers to the surface, thereby supporting phytoplankton growth. This phenomenon reflects the close relationship between the ocean physical dynamics and primary productivity [16]. During the western monsoon season (Figure 5a), the maximum chlorophyll-a concentration was detected in the Mukomuko region, ranging from 0.3 mg/m<sup>3</sup>. During transition season II (Figure 5d), the maximum chlorophyll-a concentration was recorded in the North Bengkulu region, ranging from 1.2 to 1.5 mg/m<sup>3</sup>.

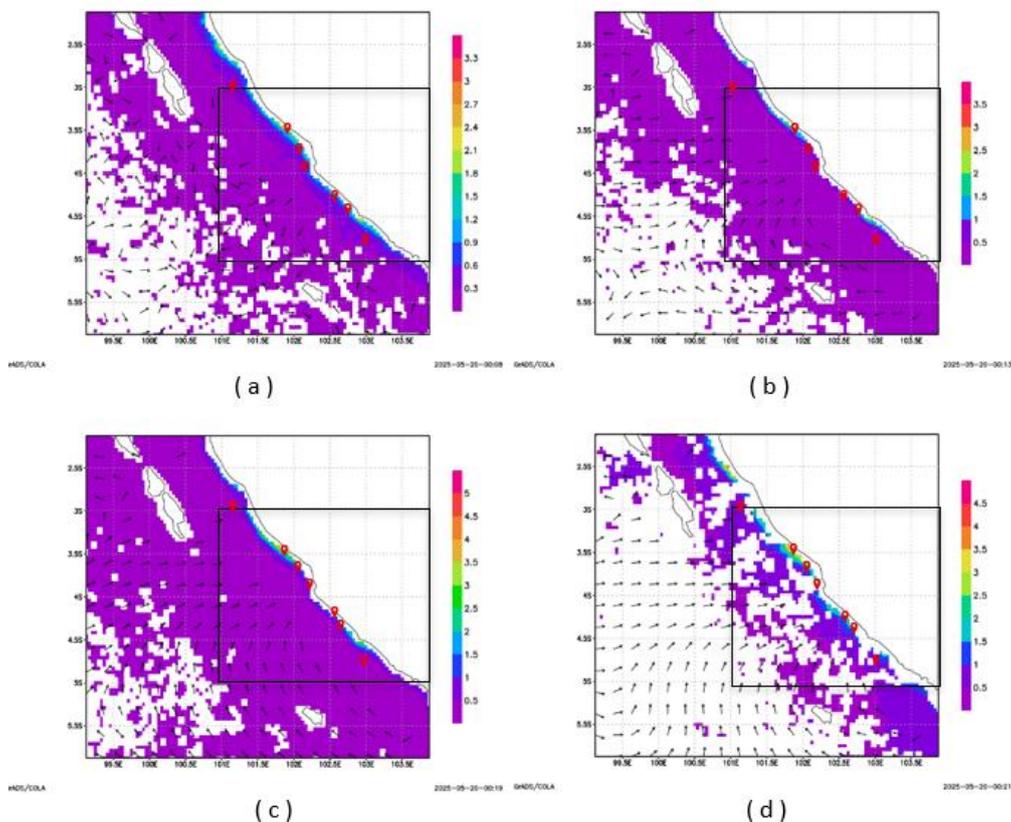


Figure 5. Relationship between Chlorophyll-a (color gradient) and ocean current (arrow direction based on seasonal variations 2013-2023: a) West Season, b) Transition Season I, c) East Season, d) Transition Season II

These findings are consistent with previous research, which shows that seasonal monsoon winds play an important role in controlling ocean-current variability in the Indonesian region [7]. A previous study [7] covering the period from 1950 to 2013 in the waters of the South China Sea revealed small shifts in the direction and intensity of winds, which have implications for changes in the surface current patterns. These shifts may be linked to an increase in the frequency of extreme weather events such as El Niño and global climate change. Previous research also supports these findings, stating that global warming causes changes in regional wind patterns that impact the ocean circulation systems in tropical regions [10].

### 3.5 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in South Bengkulu

Figure 6 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the waters of South Bengkulu during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines such as

ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue). The migration of mackerel in South Bengkulu showed an increasing movement pattern towards coastal areas, especially during the Australian monsoon and transition II. This is indicated by a significant increase in the catch yield from 2021. The migration direction tends to originate from open waters toward coastal areas, following zones with higher chlorophyll-a concentrations. Chlorophyll-a, as an indicator of primary productivity, sharply increases due to upwelling processes triggered by east monsoon winds and ocean currents flowing toward the coast. This process brings nutrients from the lower layers to the surface, increasing the availability of phytoplankton as the main food source [17]. Stable sea temperatures were not the main driving factor, but seasonal current and chlorophyll-a conditions played a crucial role in attracting mackerel migration concentrations in this area, as shown in Figure 6. Mackerel production in the waters of South Bengkulu peaked during the Second Transition Season of 2022, at approximately 42.31 tons. Conversely, the lowest production was recorded during the West Season in 2014, at approximately 5.51 tons, as shown in Figure 6.

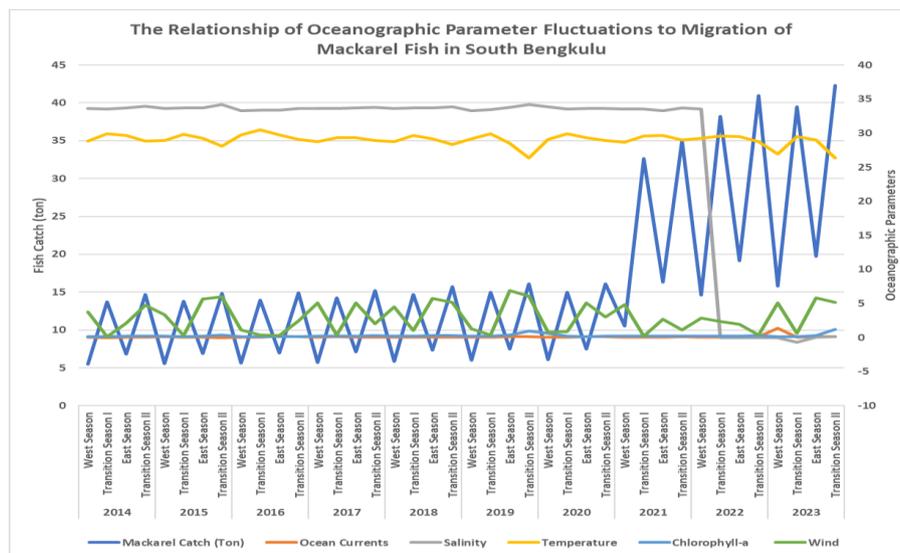


Figure 6. Migration of Spanish mackerel in South Bengkulu

Winds and currents exhibit seasonal patterns that influence fish distribution, indicating the impact of physical dynamics on

the availability of fish resources on the surface [5]. These results support previous research stating that oceanographic dynamics,

particularly upwelling and chlorophyll-a variation, significantly influence the distribution of pelagic fish such as mackerel [18]. However, unlike previous studies, which only considered annual scales, this study emphasizes that seasonal variability also plays an important role. Compared to previous studies, the increase in catch results in 2021 suggests the possibility of improved fishing gear efficiency or regional-scale environmental effects, such as La Niña, which enhance water productivity.

### 3.6 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in North Bengkulu

Figure 7 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the waters of North Bengkulu during the period 2014–2023. The left axis shows the number of fish caught (tons),

represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue). In the North Bengkulu region, mackerel migration tends to be stable, with a dominant direction of movement from south to north, following seasonal currents. This is reflected in the consistently high catch throughout the year. Fish migration towards North Bengkulu is driven by the stability of oceanographic parameters, especially chlorophyll-a concentrations, which are quite high and evenly distributed. Although wind and temperature fluctuations are low, the presence of currents flowing from productive areas to the south also brings plankton and supports the concentration of fish in this area, especially during the East Season (Figure 7).

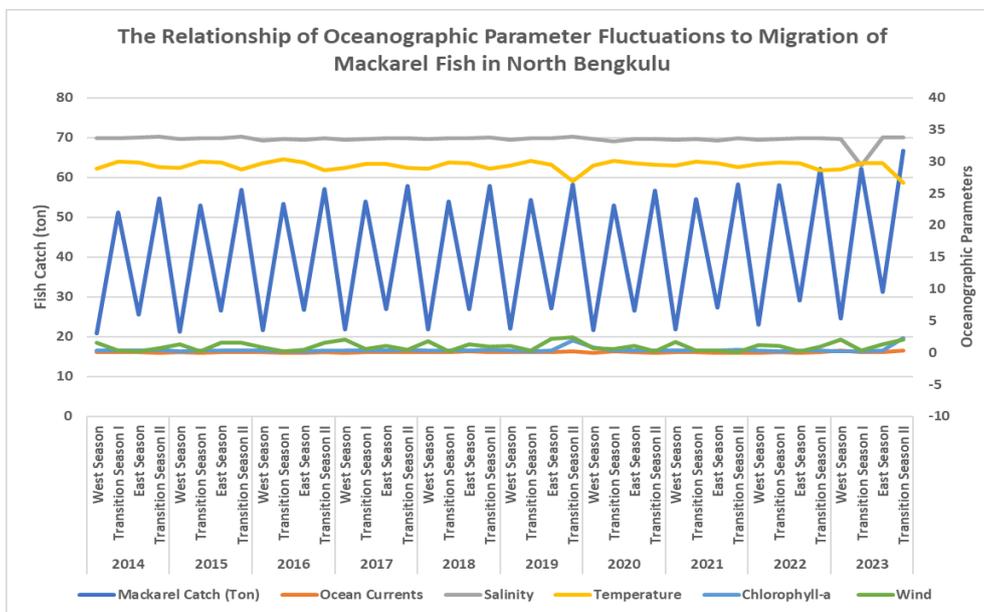


Figure 7. Fluctuations and Mackerel Migration in North Bengkulu

Based on the results of the analysis, the maximum value of mackerel catch in the North Bengkulu region was recorded as 62.28 tons in 2023, which occurred during the transition season I period. Meanwhile, the minimum catch value was recorded at 20.89 tons in 2013, which occurred during the western season. This information is shown in Fig. 7.

Chlorophyll-a values in Bengkulu Utara were higher than those in Bengkulu Selatan,

indicating better primary productivity [16], which contributed to the availability of mackerel. Ocean currents showed small fluctuations but corresponded with periods of higher catches, indicating the role of currents in the distribution of plankton as natural food [5]. These results are consistent with those of previous studies, which showed that oceanographic parameters such as chlorophyll-a and sea surface temperature strongly

influenced the concentration of large pelagic fish [19]. However, in contrast to studies that emphasize temperature as the main factor, this study indicates that chlorophyll-a and currents are more dominant in influencing catches in North Bengkulu.

### 3.7 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in Mukomuko

Figure 8 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in Mukomuko waters during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines, such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue). Mackerel migration in Mukomuko has been disrupted since 2022, as evidenced by the

sharp decline in catch yield. Previously, this area was one of the main locations for mackerel concentration, but a decrease in chlorophyll-a levels and an increase in wind speed caused the fish to migrate away from Mukomuko.

Fish tend to move south and east toward areas such as Bengkulu City or Kaur, which have higher water productivity. The Australian monsoon, which is usually beneficial, shows extreme fluctuations in wind and currents, affecting nutrient distribution and habitat stability. The migration out of Mukomuko indicates the sensitivity of the mackerel to primary productivity and physical disturbances on the sea surface, as shown in Figure 8. Based on the analyzed data, the maximum catch of mackerel in the Mukomuko region was recorded at 71.16 tons in 2018, occurring during the second transition season. Conversely, the lowest value was found in 2023 at 25.75 tons, which occurred during the East Season. A visualization of the data is shown in Figure 8.

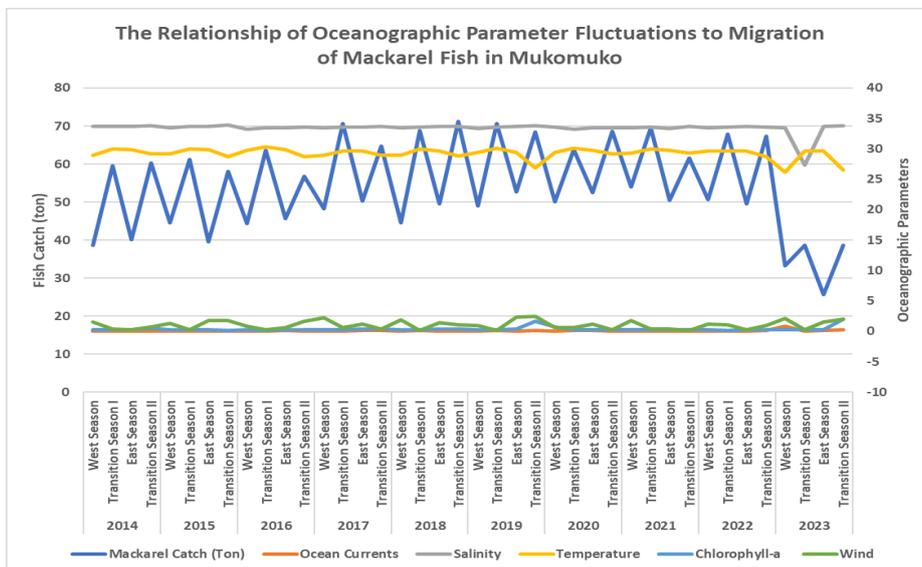


Figure 8. Relationship between Oceanographic Parameter Fluctuations and Mackerel Migration in Mukomuko

The decline in catch yield in Mukomuko was faster and more significant than that in North Bengkulu. These results indicate that this region is sensitive to changes in the marine environment, particularly biological factors, such as phytoplankton (chlorophyll) availability. These findings contradict previous studies that showed that the most important factor affecting

large pelagic fish catches is sea surface temperature [20]. During the Australian monsoon, extreme wind and current fluctuations affect nutrient distribution and habitat stability, and fish migration tends to shift to areas with higher water productivity such as Bengkulu and Kaur. This indicates that in addition to sea surface temperature, seasonal

variability in physical ocean dynamics and primary productivity also significantly influenced the distribution and abundance of mackerel. This confirms that, in addition to sea surface temperature, seasonal variability in ocean physical dynamics and primary productivity also significantly determines the distribution and abundance of large pelagic fish, such as mackerel. These findings complement and expand upon the results of the study by Mulyasari, Trisusilo, and Windirah (2023), which emphasized sea surface temperature as the primary factor by adding that the region's sensitivity to physical disturbances at the sea surface and nutrient availability are also highly important.

### 3.8 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackarel in Bengkulu City

Figure 9 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the waters off Bengkulu City during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines, such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue). Bengkulu City is one of the main centers for mackerel migration, with fish moving from the southern and offshore regions toward the coastal zone. This phenomenon was most pronounced during the Australian Monsoon and Transition II periods, when local upwelling processes driven by monsoon winds resulted in a significant increase in chlorophyll-a levels.

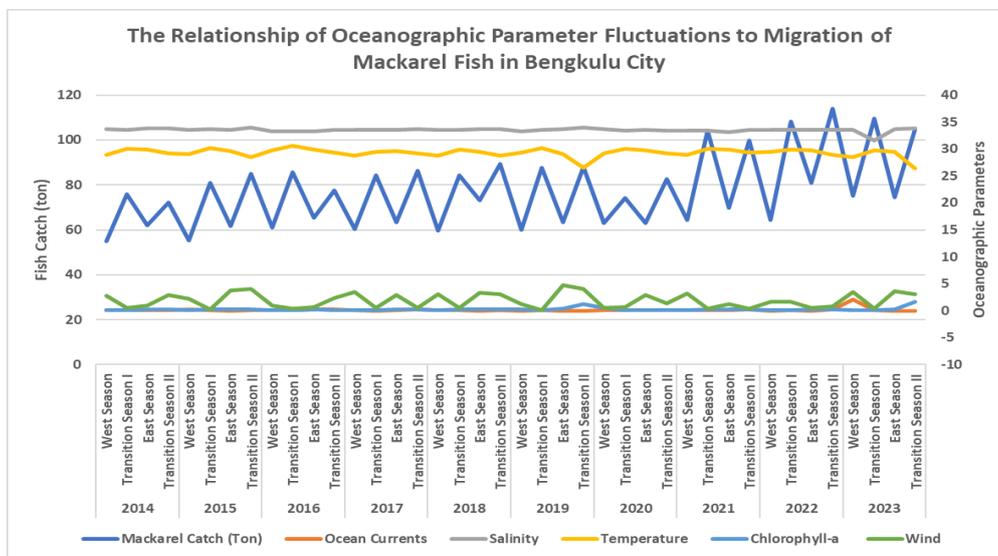


Figure 9. Relationship Between Oceanographic Parameter Fluctuations and Mackerel Migration in Bengkulu City

Stable temperature and salinity parameters help to maintain habitat comfort, but increased primary productivity is the primary factor driving mass migration. Currently supporting plankton transport and stable surface wind increase the accumulation of natural food around Bengkulu City waters, making it a seasonal migration and aggregation zone for mackerel, as shown in Figure 9. Based on catch data, the maximum production value of mackerel in the Mukomuko region was recorded

as 113.91 tons in 2022, which occurred during the second transition season. The minimum value was recorded at 54.97 tons in 2014, which occurred during the western season, as shown in Figure 9.

The phenomenon of mackerel migration to the waters of Bengkulu City during the Australian Monsoon and Transition II is not only influenced by increased chlorophyll-a due to local upwelling but also by complex interactions between physical and biological factors that

create optimal habitat conditions. Stability in temperature and salinity maintains a comfortable environmental balance for fish, while ocean currents that support plankton transport enhance the availability of natural food sources. Additionally, stable surface winds during this period enhance nutrient circulation and distribution, thereby prolonging the duration and intensity of the high-productivity zones. These conditions create ecosystem hotspots that attract mackerel to migrate and gather seasonally, thereby increasing the potential of fisheries in the region. Previous research has shown that chlorophyll-a concentration and sea surface temperature have a significant influence on the distribution of large pelagic fish in tropical Indonesia. These findings support the results of Bengkulu City, where chlorophyll-a fluctuations and wind

dynamics (as triggers for local upwelling) are closely correlated with increases in mackerel catches [19]

### 3.9 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in Kaur

Figure 10 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the Kaur waters during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines, such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue).

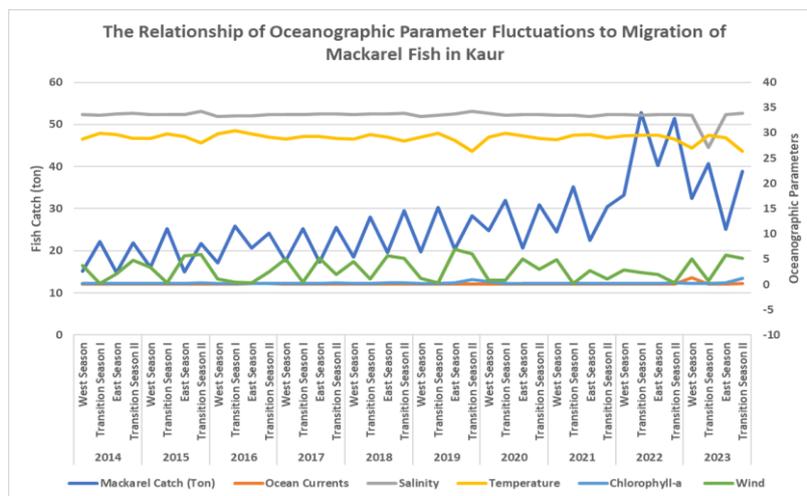


Figure 10. Relationship between Oceanographic Parameter Fluctuations and Mackerel Migration in Kaur

In the Kaur region, mackerel migration has increased since 2018, with dominant movement from the middle of the sea to the east coast. This condition aligns with the increase in chlorophyll-a and intensification of the eastern monsoon winds, which trigger upwelling and bring nutrients to the surface. Catch yields have

Oceanographic factors, such as chlorophyll-a and currents, play a dominant role in migration patterns in this region, as shown in Figure 10. The highest mackerel catch in the Kaur region was recorded at 52.86 tons in 2022, which occurred during the first transition season. Meanwhile, the lowest catch was recorded at

increased along with improvements in oceanographic conditions, particularly during the eastern monsoon season. Sea currents flowing from the southeast to the northwest also support the movement of natural prey toward coastal areas, creating natural migration routes for mackerels.

14.82 tons in 2014, which occurred during the East Season. These data are presented in Fig. 10. The Kaur region shows a very strong response to seasonal oceanographic dynamics, especially during the East. The increase in catch since 2018 indicates that this region has become a temporarily favorite habitat for mackerel,

following upwelling trends and high primary productivity. In addition to chlorophyll-a and wind as the main triggers, the presence of a stable sea current from southeast to northwest also supports the food concentration and ecological comfort required for this species.

Previous research has confirmed that the Australian Monsoon in the Java and Bali Seas increases chlorophyll-a concentrations owing to

upwelling processes, which in turn boosts pelagic fish catches. This is consistent with trends in Kaur, where fluctuations in chlorophyll-a and increased winds since 2018 appeared to be the main drivers of the increase in mackerel catches [20].

### 3.10. The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in Seluma

Figure 11 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the Seluma waters during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines, such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue).

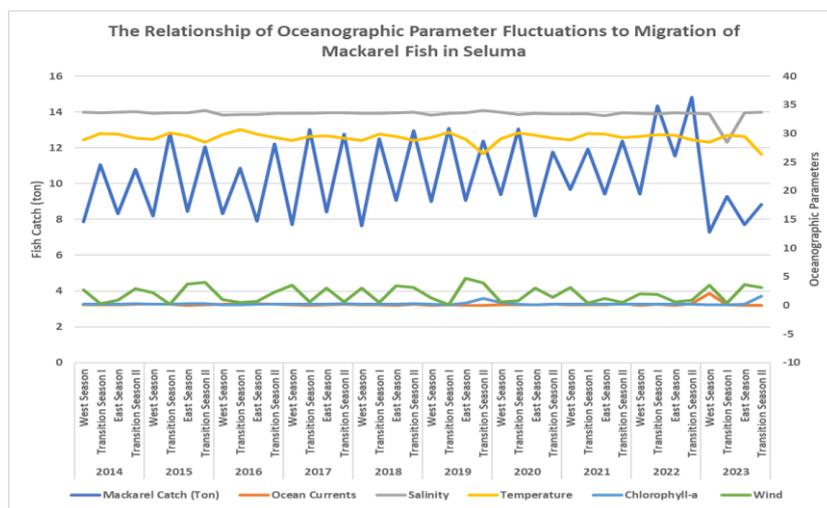


Figure 11. Relationship between Oceanographic Parameter Fluctuations and Mackerel Migration in Seluma

In the Seluma region, mackerel migration activity is more limited, with catch results tending to be stable and low. The direction of fish migration does not appear to target this region significantly, which may be due to less dynamic oceanographic conditions. Chlorophyll-a and wind showed little fluctuation, whereas temperature and salinity remained relatively constant throughout the year. This indicates that there is no sufficiently strong oceanographic stimulus to attract migrating fish to the Seluma. Therefore, mackerel tend to pass through or not stay long in this region, and migration is more active toward areas with higher primary productivity, such as Bengkulu City or North Bengkulu, as shown in Figure 11. Based on the data obtained, the highest

mackerel catch in the Seluma region was recorded as 14.36 tons in 2022, which occurred during the first transition season. Conversely, the lowest value was recorded at 7.71 tons in 2023, which occurred during the East Season. The data visualization is shown in Figure 11.

The Seluma region is an example of an area less responsive to oceanographic dynamics. The low variability of oceanographic parameters, such as chlorophyll-a and wind, results in limited environmental stimuli required to attract mackerel to migrate and settle. Thus, mackerel migrate through this region only as a transit point, rather than settling. Previous research in Palabuhanratu showed that the Australian monsoon is the main season for pelagic fish catches, and is related to chlorophyll-a dynamics

and sea temperature [5]. However, in Seluma, oceanographic factors only showed limited influence, indicating that other factors, such as fishing technology and fishing activities, are more dominant in determining fluctuations in mackerel catch yields.

### 3.11 The Relationship of Oceanographic Parameter Fluctuations to Migration of Spanish mackerel in Central Bengkulu

Figure 12 shows the relationship between fluctuations in oceanographic parameters and mackerel catches in the waters of Central Bengkulu during the period 2014–2023. The left axis shows the number of fish caught (tons), represented by the blue line. The right axis shows oceanographic parameter values, represented by several colored lines, such as ocean currents (orange), salinity (gray), sea surface temperature (yellow), chlorophyll-a (green), and wind speed (light blue). The migration pattern of mackerel in Central Bengkulu shows a static graph with stable and relatively low catch results. This indicated that fish did not actively migrate to this area in large numbers. Oceanographic parameters such as temperature, salinity, and currents show high stability, whereas chlorophyll-a and wind experience slight fluctuations that are not significant enough. Migration to this region is likely part of a regional migration route rather than a permanent settlement. Thus, mackerel migration to Central Bengkulu is not driven by oceanographic parameters but is more likely influenced by other factors, such as fishing

activities or environmental disturbances in the surrounding areas, as shown in Figure 12. Based on the results of data analysis, the highest mackerel catch in the Central Bengkulu region was recorded at 15.22 tons in 2021, which occurred during the transition season I. Meanwhile, the lowest catch was recorded at 5.34 tons in 2023, which occurred during the East Season. This information is presented in Fig. 12.

Central Bengkulu showed high stability in oceanographic parameters, but this was not accompanied by a surge in catch yield. This indicated that stability in temperature and salinity does not guarantee fish aggregation. The lack of fluctuations in chlorophyll-a and wind causes this region to not experience significant upwelling processes, which are important for attracting pelagic fish. It is likely that mackerel passes only through this region as part of its regional migration routes. Therefore, it is important to evaluate non-oceanographic factors that may play a more significant role in this region, such as fishing pressure, human activities, and environmental degradation, which are not reflected in physicochemical parameters.

Previous studies have revealed that sea surface temperature is a major factor affecting the catch of large pelagic fish in northern Indonesian waters [20]. However, in Central Bengkulu, stable temperature and salinity did not result in an increase in catch, indicating the dominant role of nonoceanographic factors in this region.

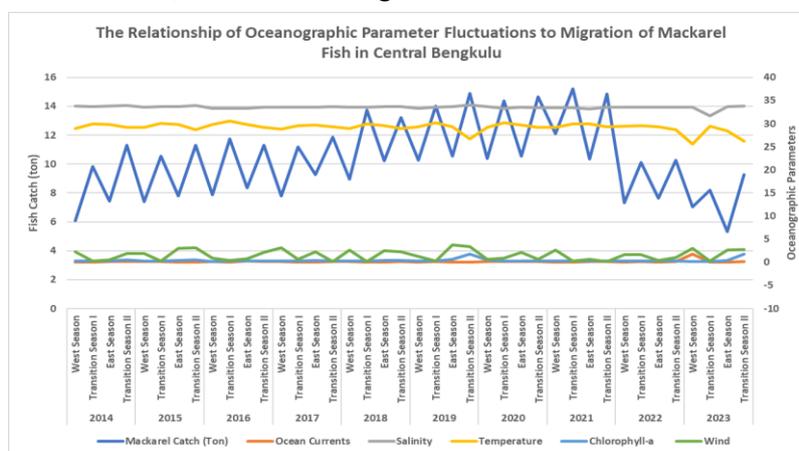


Figure 12. Relationship between Oceanographic Parameter Fluctuations and Mackerel Migration in Central Bengkulu

#### 4. Conclusions

This study showed that the migration of mackerel in Bengkulu waters is greatly influenced by seasonal oceanographic parameters, particularly chlorophyll-a and wind. Temperature and salinity parameters tended to be stable throughout the year and did not have a significant influence on fish distribution. A significant increase in mackerel catch was recorded during the Australian Monsoon and Transition II periods, particularly in the Kaur, Bengkulu City, and North Bengkulu regions, which experienced a surge in chlorophyll-a levels due to upwelling processes triggered by eastern monsoon winds. Spatially and temporally, the analysis results show that the highest current speeds occur during the east monsoon season, which is in line with the dominant southeast wind direction. Minimum salinity was detected in Seluma during the west monsoon season with values of 29.1–29.4 PSU, while maximum salinity occurred during Transition II in Seluma and South Bengkulu, ranging from 30.2–30.3 PSU. The highest sea surface temperature was recorded in Seluma during the west monsoon season, ranging from 29.7 to 30°C, and the minimum temperature reached 25.2°C in Central Bengkulu during the second transition season. Chlorophyll-a concentrations showed the highest values of 1.2–1.5 mg/m<sup>3</sup> in North Bengkulu during the second transition season, while the lowest values were recorded in Mukomuko during the west monsoon season, around 0.3 mg/m<sup>3</sup>. These findings confirm that the dynamics of chlorophyll-a and seasonal winds are the primary factors shaping the seasonal migration patterns of mackerel in the study area, and are more dominant than temperature and salinity.

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**Author contribution:** Compile research data, collected and processed oceanographic, fish catch data, performed data analysis: Author 1; Supervised the overall research process, validated analytical methods, provided scientific input during manuscript development: Author 2 and Author 3; Provided fish catch data from the Marine and Fisheries Service of Bengkulu Province and contributed to the regional policy context; Author 4

**Competing interest:** We, as authors, declare that we have no competing interests

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