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Research Article

Seasonal Migration Zone of Skipjack Tuna (*Katsuwonus pelamis*) in the South Java Sea Using Multisensor Satellite Remote Sensing

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Skipjack tuna (*Katsuwonus pelamis*) is the most dominating tuna species caught in the Indian Ocean. However, tuna fishermen in the Indian Ocean still face difficulties determining potential skipjack tuna fishing grounds due to limited geographic information. An attempt to improve information regarding potential skipjack tuna fishing grounds is through modeling the SST, SSC, SSH, and SSS oceanographic parameters with skipjack tuna distribution using GIS. The characteristics of the skipjack tuna habitat can be found through the generalized additive model (GAM) statistical analysis using data of skipjack tuna catch and oceanographic parameters from satellite imagery. The integrated GIS and GAM methods can improve the study of the habitat of skipjack tuna species. Therefore, this research is aimed at analyzing the condition and SST, SSC, SSH, and SSS variations in 2016-2021 in the South Java Sea; at predicting the correlation of SST, SSC, SSH, and SSS towards skipjack tuna catch in 2016-2021 in the South Java Sea using GAM; and at creating a map of skipjack tuna seasonal migration zones. The data included skipjack tuna catches, number of trips, and skipjack tuna fishing coordinates in 2016-2021 from PPS Cilacap and PPP Pondokdadap. The oceanographic parameter data in 2016-2021 was derived from Aqua MODIS level 3 (SST and SSC) and CMEMS (SSH and SSS) satellite imagery. The results showed that the average values of oceanographic parameters at skipjack tuna fishing ground coordinates in the South Java Sea (2016-2021) were SST (26.050-30.816°C), SSC (0.094-0.564 mg/m^3), SSH (0.268-0.639 m), and SSS (33.075-34.514 psu). The best GAM modeling was the combination of four oceanographic parameter variables with an AIC value of 45357.92. Skipjack tuna in the South Java Sea migrates southeast during the west monsoon season to the first transitional season and tends to migrate northwest during the east monsoon season to the second transitional season.

1. Introduction

Indonesia is one of the largest producers of tuna in the world, producing about 16% of the world's total tuna supply [1]. Tuna fish has become the main species in Indonesia, with an export value reaching US$ 677.9 million in 2017. The production of skipjack tuna (*Katsuwonus pelamis*) caught in the Indian Ocean is 13,000 tons each year out of the total national catch, making it the species that produces the most than other tuna species. In addition, in 2012-2016, skipjack tuna dominated the catch of tuna species with fishing grounds in the Indian Ocean, which reached 51.4% of 150,062 tons [2].

Skipjack tuna is the fastest-growing tuna species, growing to over 1 m in length and gaining an average weight of up to 18 kg [3]. Skipjack tuna is a fast-swimming pelagic fish that inhabits most tropical and subtropical waters. Skipjack tuna performs horizontal migration over 1,000 nautical miles. Skipjack tuna's habitat is associated with a sea surface temperature (SST) range between 18 and 30°C with a preferred range between 23 and 28°C. Their suitable habitat is restricted to air masses that are relatively warm, have a high oxygen content, and are close to cooler air (below the thermocline) in order for them to release excess metabolic heat [4].

Skipjack tuna distribution in Indonesian waters includes the south of Java, west of Sumatra, and north of Aceh, Sulawesi, Arafura, Banda, Maluku, Flores, Halmahera, Tomini Bay, and Cenderawasih Bay [5]. The South Java Sea, which belongs to the Fisheries Management Area of the Republic of Indonesia 573 (WPPNRI 573), has long been known to have high tuna resources [6].

Fishermen in the Indian Ocean face difficulties fishing because of the limited geographic information on potential skipjack tuna fishing grounds. Spatial information on fishing grounds is significant in determining target and nontarget fish habitats and supporting the program of sustainable tuna fishery resource management [7]. Efforts to improve spatial information provision in fishing grounds are made through remote sensing technology and geographic information system (GIS) implementation. GIS is an approach specifically designed to organize, manipulate, visualize, and analyze various data to provide the information needed. The GIS approach facilitates the study and understanding of fisheries and marine resources both spatially and temporally. One GIS application is modeling the correlation of oceanographic parameters and the distribution of fish [8].

The principle of estimating potential fishing grounds is to find the correlation and suitability of oceanographic parameters with the presence of fish schools [9]. This principle is based on the fact that fish distribution and abundance are closely influenced by oceanographic parameters. Sea surface temperature and chlorophyll-a are the most significant oceanographic variables influencing tuna fish migration patterns and presence [10]. Sea surface temperature significantly affects the physiology, abundance, and distribution of skipjack tuna and thus works as an indicator in predicting the presence of fish in the water column. Chlorophyll-a is a parameter used for determining primary productivity in the ocean. The chlorophyll-a concentration can indicate the presence of phytoplankton and zooplankton, which act as producers of marine organisms in the food chain. The chlorophyll-a concentration also varies because it is influenced by differences in sunlight intensity [11]. In addition, other oceanographic parameters like salinity and sea surface height (SSH) also affect fish abundance. Salinity is a nutrient condition and primary productivity indicator [12]. SSH or sea level can reflect ocean phenomena such as front and dynamic of current, eddy, convergence, and upwelling as a gathering place for fish [13].

Statistical modeling in GIS has been widely used to provide a quantitative description and prediction of suitable marine resource habitats. According to [9], the fish distribution and abundance variables with the oceanographic parameter variable generally form a nonlinear relationship, so statistical approaches such as the generalized additive model (GAM) are more suitable. GAM is a statistical regression model that can predict the nonlinear and nonparametric relationship between response variables and predictor variables [14, 15]. The habitat characteristics of tuna fish can be analyzed using GAM with fish catch and oceanographic parameter data from satellite imagery. GIS and GAM statistical models can improve studies about fish habitats [16]. Therefore, this research was conducted to add information regarding mapping potential fishing locations and movement patterns of skipjack tuna based on GIS and GAM in the South Java Sea.

2. Materials and Methods

2.1. Study Area and Data Source. The research area is located in the South Java Sea at coordinates 102° 34′ 40.192″-114° 31′ 47.578″ E and 6° 48′ 8.965″-12° 8′ 22.537″ S (see Figure 1). The South Java Sea is a part of the East Indian Ocean (EIO), and it has unique characteristics. There are several factors that influence the characteristics of EOI such as the Asia-Australia monsoon, complex composition of water masses, and climate change phenomena like IOD and ENSO [17]. The Asia-Australia monsoon contributes on the variation of oceanographic parameters seasonally [18]. Water masses in the South Java Sea consist of a combination between Pacific Ocean and Indian Ocean seawater masses that are carried by Indonesian Throughflow [19]. Indonesian Throughflow impacts the seasonally changing temperature, salinity, chlorophyll-a variation, and distribution of fish. Research by [20] stated that the high concentration of chlorophyll-a produces high catches of skipjack tuna.

The fish unloading inspection data used includes catch data, number of fishing trips, and coordinates of skipjack tuna fishing in 2016-2021 from PPS Cilacap and PPP Pondokdadap. Oceanographic parameter data of sea surface temperature and chlorophyll-a are from Aqua MODIS level 3, monthly temporal resolution, $4\,\text{km} \times 4\,\text{km}$ spatial resolution downloaded from NASA Ocean Color website. Oceanographic parameters sea surface height and salinity are from CMEMS, monthly temporal resolution, spatial resolution $0.083^\circ \times 0.083^\circ$ downloaded from https://marine.copernicus.eu/. The research data processing utilized is presented in Table 1.

2.2. Catch per Unit Effort (CPUE). The CPUE calculation is aimed at determining the value of the catch rate of fishing effort based on the division of fish catch towards effort. The fishery data obtained from the port is sorted, leaving behind information for skipjack tuna species. Data processing is continued with monthly skipjack tuna CPUE analysis using the following equation [21]:

$$\text{CPUE}_i = \frac{c_i}{f_i}. \tag{1}$$

2.3. Oceanographic Parameter Data. Imagery data of oceanographic parameters is cropped to focus on the study area using SeaDAS 7.5.3. SST and SSC values are exported (export mask pixels) and saved as text document (.txt) files. The *.txt file was further opened using Microsoft Excel to remove blank data (NaN). SST, SSC, SSH, and SSH imagery

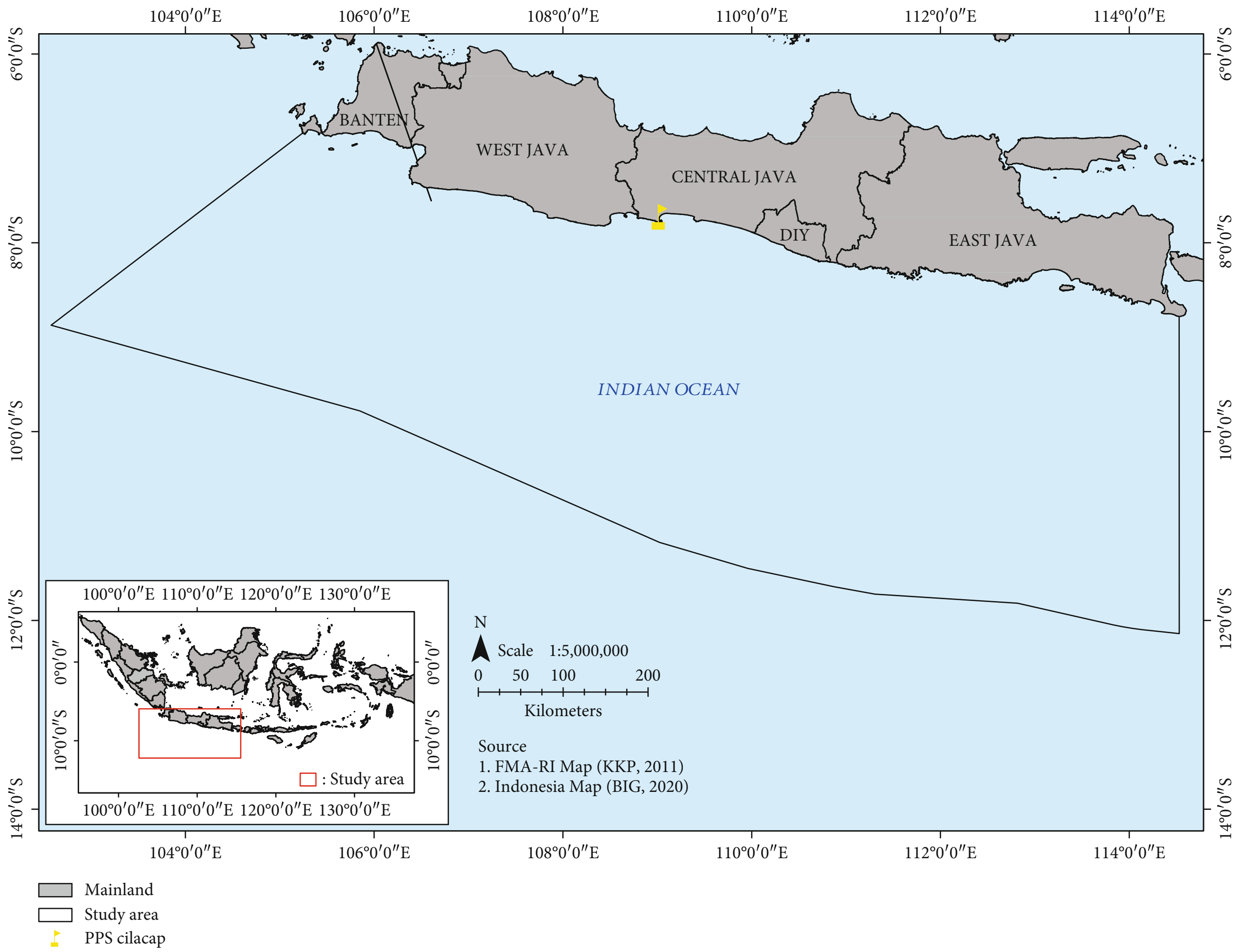

Figure 1: Study area.

Table 1: Research tools.

No.	Name	Function
1.	SeaDAS 7.5.3	Software for cropping and exporting mask pixels of sea surface temperature and chlorophyll-a data
2.	ArcGIS 10.8	Software for satellite imagery interpolation, map generation of potential fishing locations, and skipjack tuna movement patterns
3.	RStudio 4.1.1	Software for performing generalized additive model statistical models
4.	Microsoft Excel 2019	Software for processing skipjack tuna fishery data and making graphs

data processing was continued using ArcGIS 10.8 for the inverse distance weighted (IDW) interpolation. The IDW method is assumed to provide interpolated values similar to the surrounding sample data and is the most optimal interpolation method compared to other methods [22]. The four oceanographic parameter distributions interpolated from IDW imagery are further extracted (Extract Multi Values to Point (Spatial Analyst)) using fishing ground coordinates.

2.4. Generalized Additive Model (GAM) Analysis. GAM is used to determine the effects of oceanographic parameter variables SST, SSC, SSH, and SSH on the abundance and distribution of skipjack tuna resources. GAM is modeled using the MGCV package in RStudio 4.1.1 software. The MGCV package provided a generalized additive modeling function in a penalized spline regression modeling framework using generalized cross-validation to identify smoothed correlations between predictor and response variables [23]. The model equation in GAM used in this research is as follows [24]:

$$g(u_i) = a_o + s_1(\mathrm{SST}) + s_2(\mathrm{SSC}) + s_3(\mathrm{SSH}) + s_4(\mathrm{SSS}), \quad (2)$$

where are g is the link function, u_i is the value of dependent variable, and a_o is the model constant.

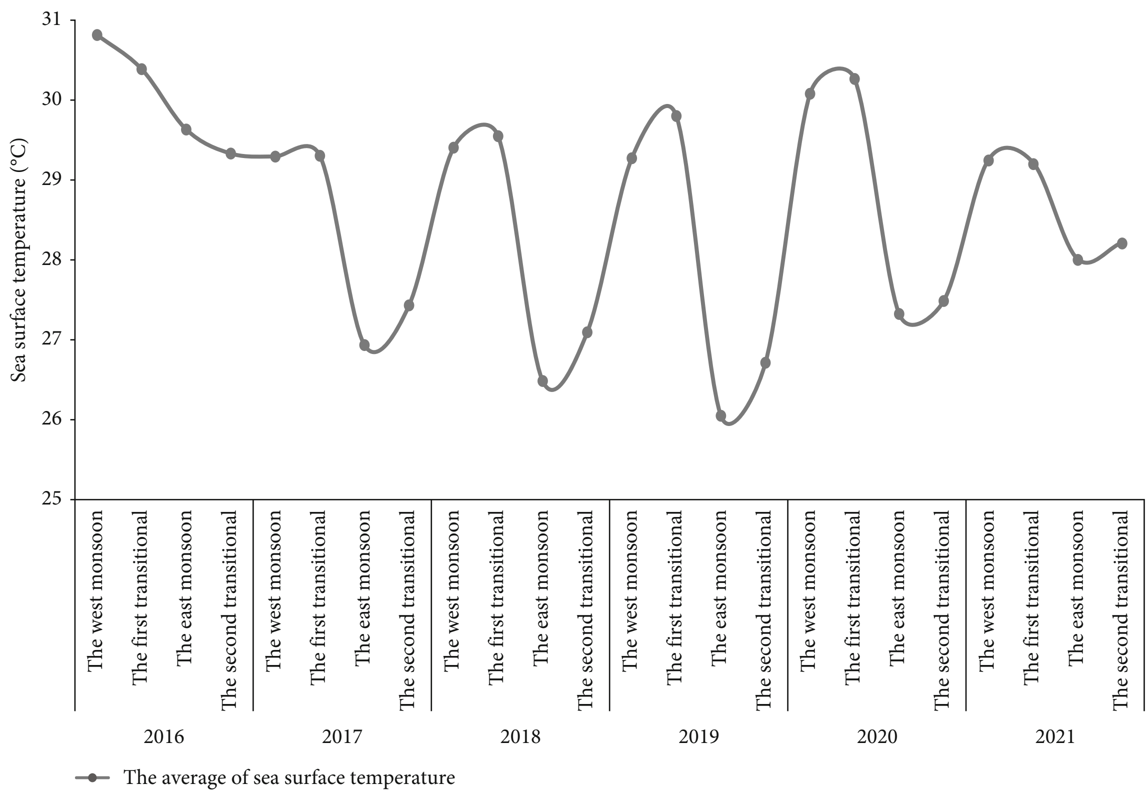

Figure 2: The average SST during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea.

Data which includes oceanographic parameter values (predictor variable) and CPUE of skipjack tuna (response variable) for modeling and creating the GAM equation in RStudio 4.1.1 must be converted into the comma-separated value (CSV) format. The output obtained from GAM analysis included a summary model, AIC value, and smoothing curve. The summary model consisted of information about cumulative deviance explained (CDE) and P value.

Determining the best model decision for GAM modeling is based on the AIC and CDE values. The predictor variable is considered to significantly affect the response variable when the AIC value is low, the CDE value is high, and the P value is less than 0.01. On the smoothing curve, the x-axis indicates the variable, while the y-axis has an important role. A horizontal line at zero indicates no parameter effect. GAM function modeling above the zero axis indicated a strong (positive) influence of a parameter and vice versa [25].

2.5. Mapping of Seasonal Migration Zone of Skipjack Tuna. Mapping of potential fishing grounds and seasonal migration zone of skipjack tuna is done on ArcMap. The distribution of SST, SSC, SSH, and SSS oceanographic parameters from IDW interpolation is reclassified to obtain a new class using the optimal value of each oceanographic parameter resulting from curve smoothing GAM. Then, weighted overlay is done by using a combination of oceanographic parameter raster that was determined from the best results of GAM model analysis. The weighted overlay method is chosen because every parameter in nature affects something to different degrees [26]. The weighted overlay process results are the potential fishing ground map of skipjack tuna. Afterward, the mapping of skipjack tuna movement patterns in the South Java Sea is based on reference to the potential fishing ground map that has been made and the location points of skipjack tuna fishing obtained from PPS Cilacap and PPP Pondokdadap.

3. Results and Discussion

3.1. Sea Surface Temperature (SST). Sea surface temperature is an oceanographic parameter that plays a significant role in the metabolism and reproduction of marine organisms, especially fish. The SST distribution provides important information about the front, upwelling, and fishing grounds [27]. The average of SST for each season during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea is calculated and graphed using Microsoft Excel, and it showed seasonal variations (see Figure 2). It is reinforced by research [28], stating that SST follows a seasonal pattern and is affected by meteorological conditions such as sunlight intensity, wind speed, precipitation, evaporation, and humidity.

The average SST during 2016-2021 ranged from 26.050 to 30.816°C. The highest SST occurred during the Asian monsoon (the west monsoon season in December-February and first transitional season in March-May), while the lowest SST occurred during the Australian monsoon (the east monsoon season in June-August and second transitional season in September-November) (see Figures 2 and 3). The high SST during the Asian monsoon was due to the movement of the sun's

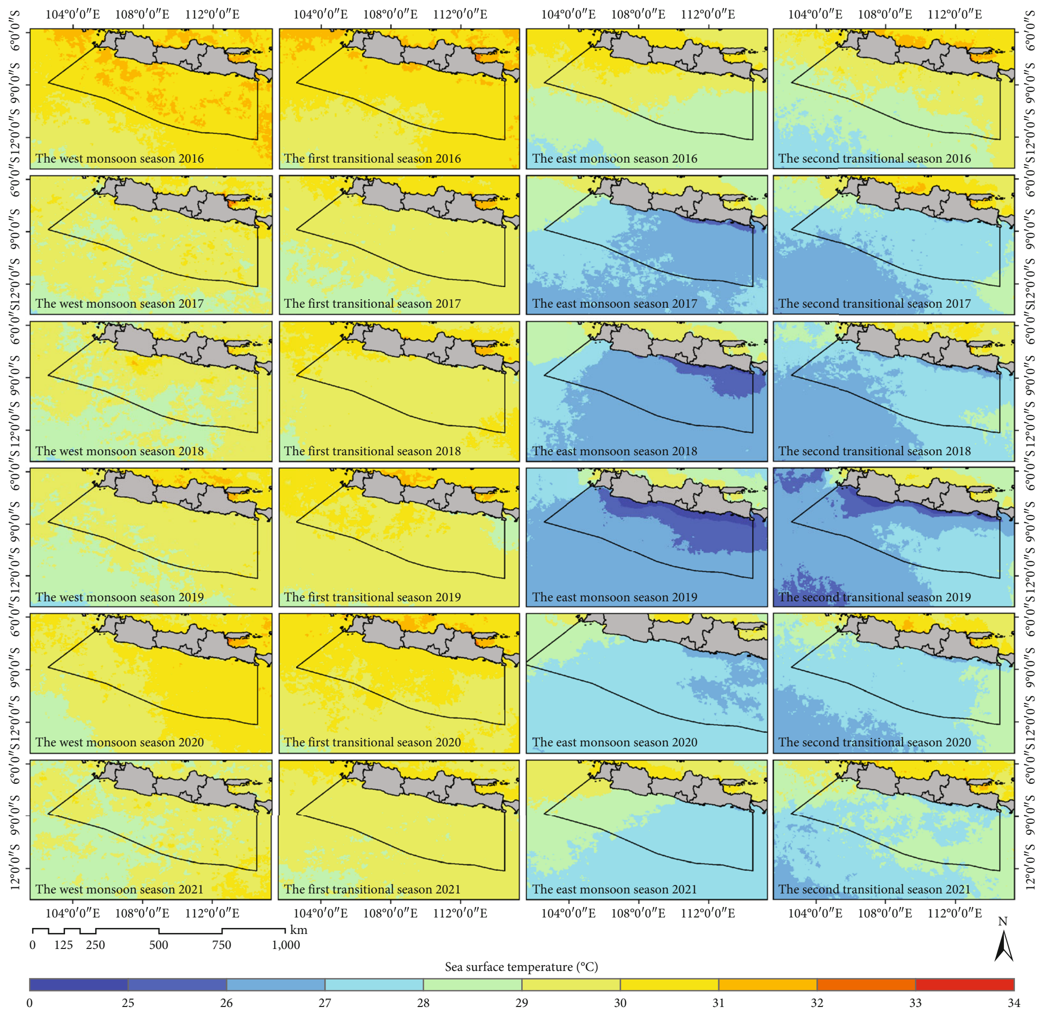

Figure 3: Map of seasonal SST during 2016-2021 in the South Java Sea.

position close to the equator. Therefore, solar radiation in the Indian Ocean is quite high. During the Australian monsoon, the sun's position is in the northern part of the earth. Thus, the South Java Sea received weaker solar radiation, making the SST range lower than the Asian monsoon. The SST during the Asian monsoon was also affected by the equatorial counter current. The equatorial counter current carries a warm water mass that moves along the southwest coast of Sumatra and joins the south equatorial current from the east [29].

3.2. Sea Surface Chlorophyll-a (SSC). Chlorophyll-a is a green pigment found in algae, cyanobacteria, and plants. It plays a significant role in the photosynthesis process in a body of water [30]. Primary productivity in the waters is determined by chlorophyll-a content. The distribution and concentration of chlorophyll-a closely relate to phytoplankton as food for fish larvae [31]. A graph about the average of SSC during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea indicates that chlorophyll-a concentration fluctuates seasonally (see Figure 4).

The average SSC in the South Java Sea in 2016-2021 ranged from 0.094 to 0.564 mg/m^3. The highest average SSC concentration occurred during the Australian monsoon, while the lowest average SSC occurred during the Asian monsoon (see Figures 4 and 5). It is strengthened by [32], who stated that the pattern of chlorophyll-a changes is influenced by seasonal wind movements. Winds from the southeast during the Australian monsoon cause currents to move along the coast towards the offshore, which triggers upwelling. Research by [33] also stated that current movements and upwelling have a dominant influence on chlorophyll-a concentration. Chlorophyll-a content is also affected by household organic waste, agriculture, aquaculture, and other activities.

Graphs of the SST and SSC average (see Figures 2 and 4) show an inversely proportional relationship; if the average SST is high, the average SSC is low, and vice versa. It is presumably because higher wind speeds will cause the mixing process or stirring of the water mass to accelerate. The mixing process causes low-temperature and nutrient-rich water masses from the lower layers to rise to the surface. Therefore, the sea surface temperature becomes cold [34].

3.3. Sea Surface Height (SSH). The average SSH during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea has a fluctuating pattern (see Figure 6). SSH

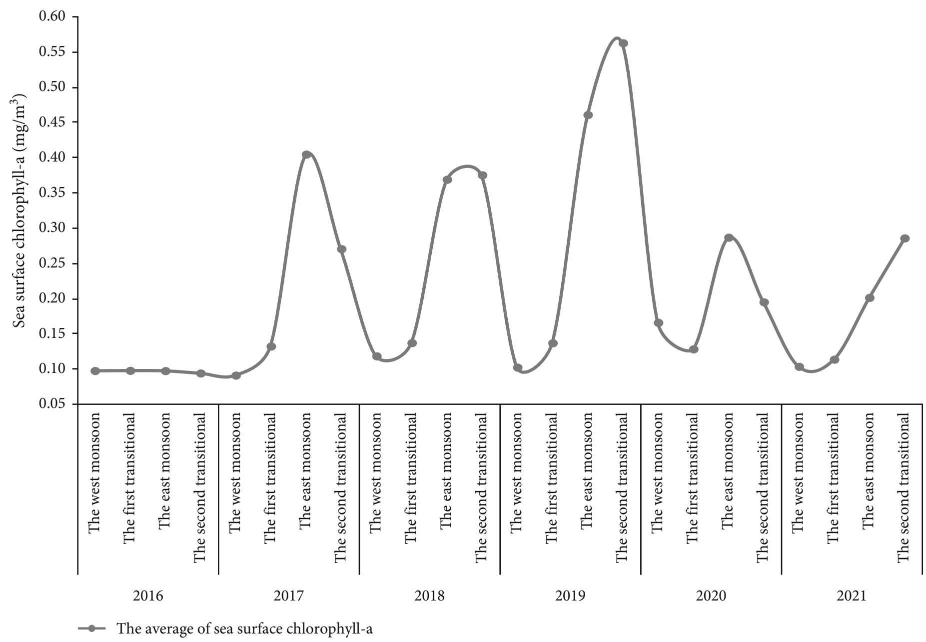

FIGURE 4: The average of SSC during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea.

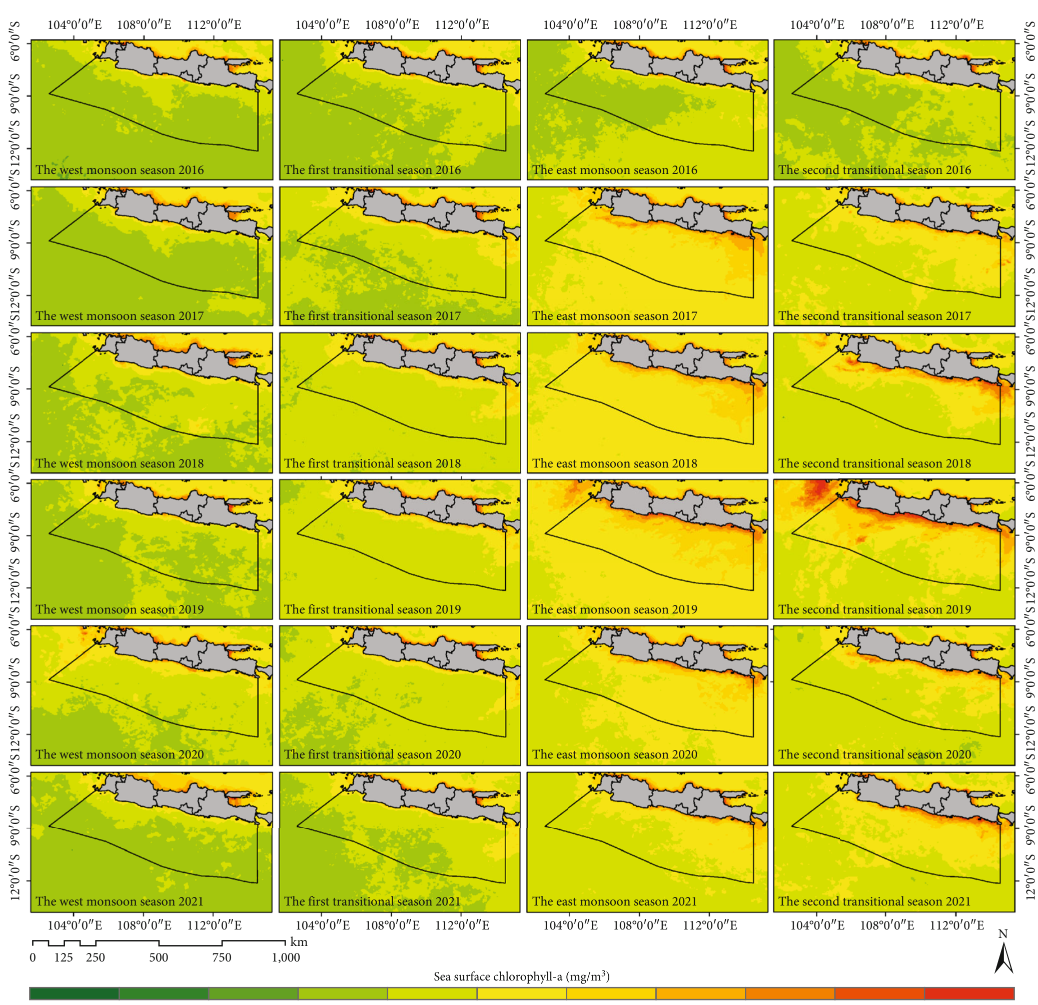

FIGURE 5: Map of seasonal SSC during 2016-2021 in the South Java Sea.

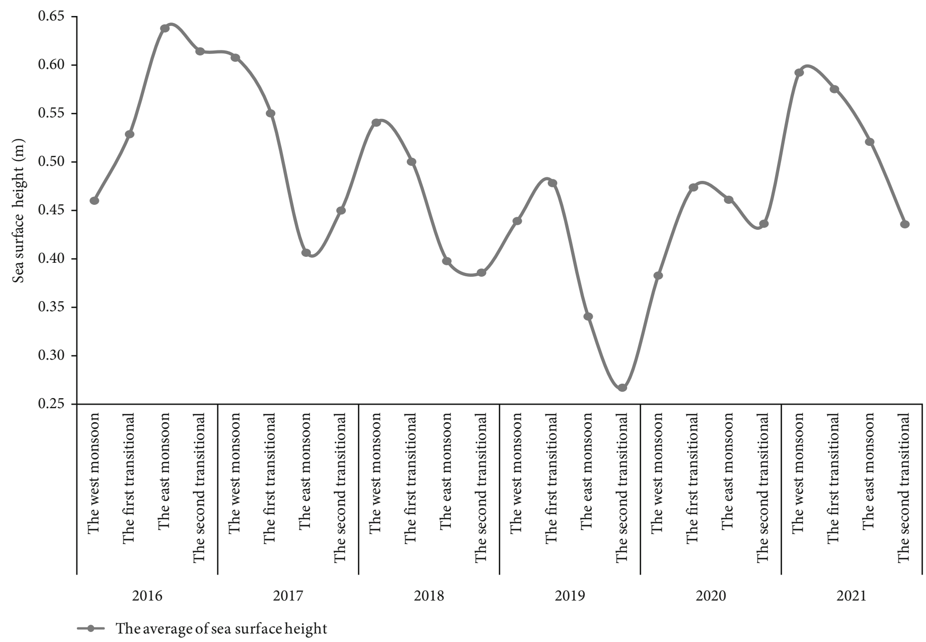

Figure 6: The average SSH during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea.

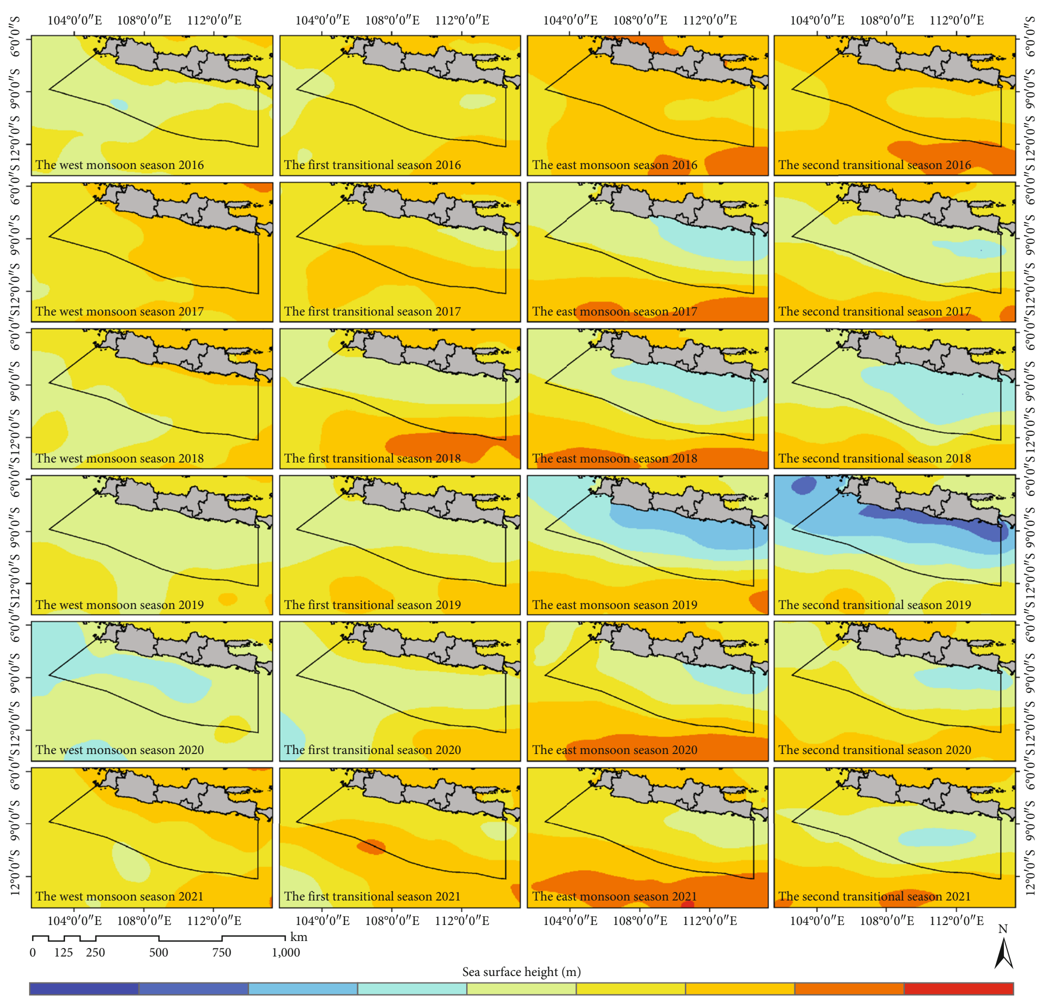

Figure 7: Map of seasonal SSH during 2016-2021 in the South Java Sea.

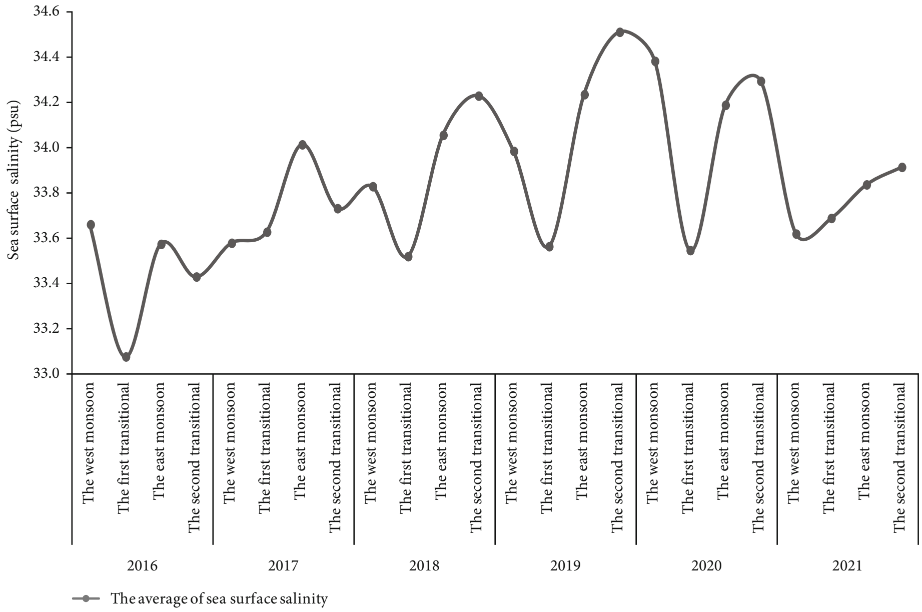

Figure 8: The average SSS during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea.

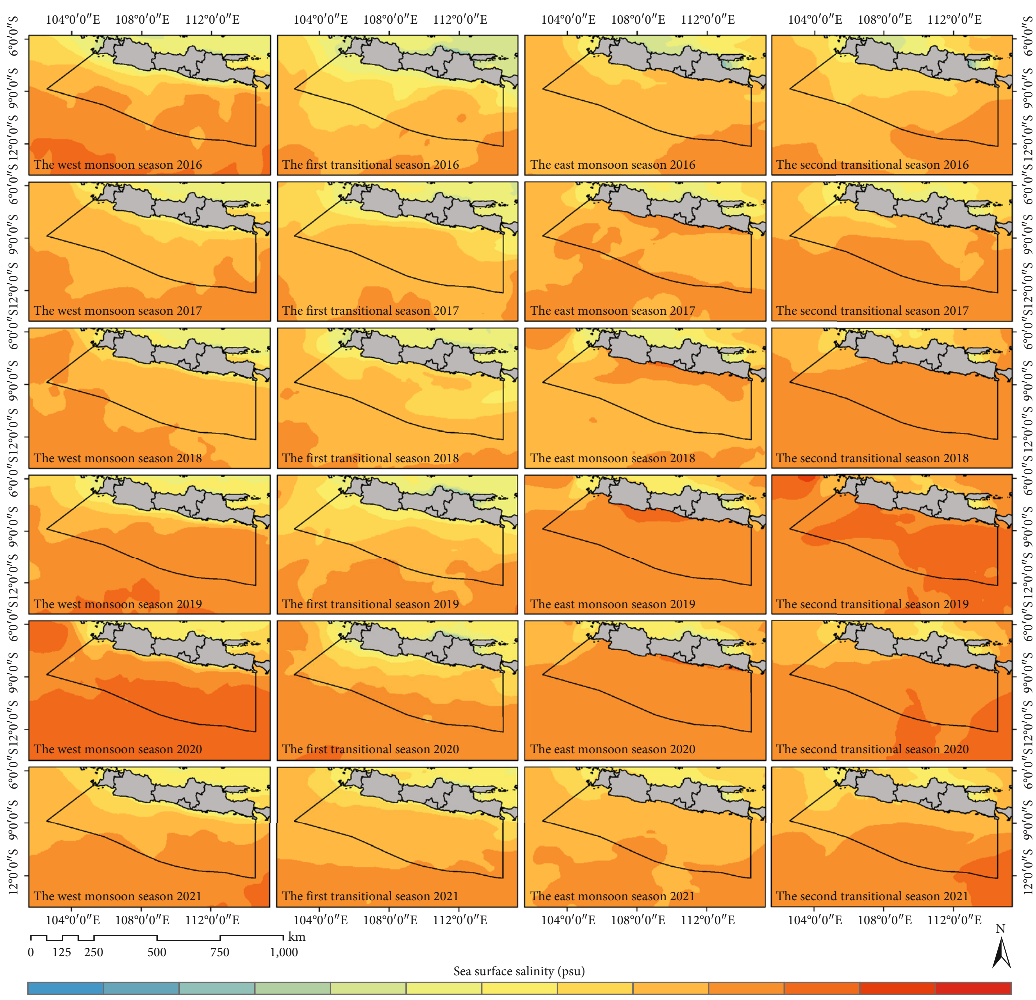

Figure 9: Map of seasonal SSS during 2016-2021 in the South Java Sea.

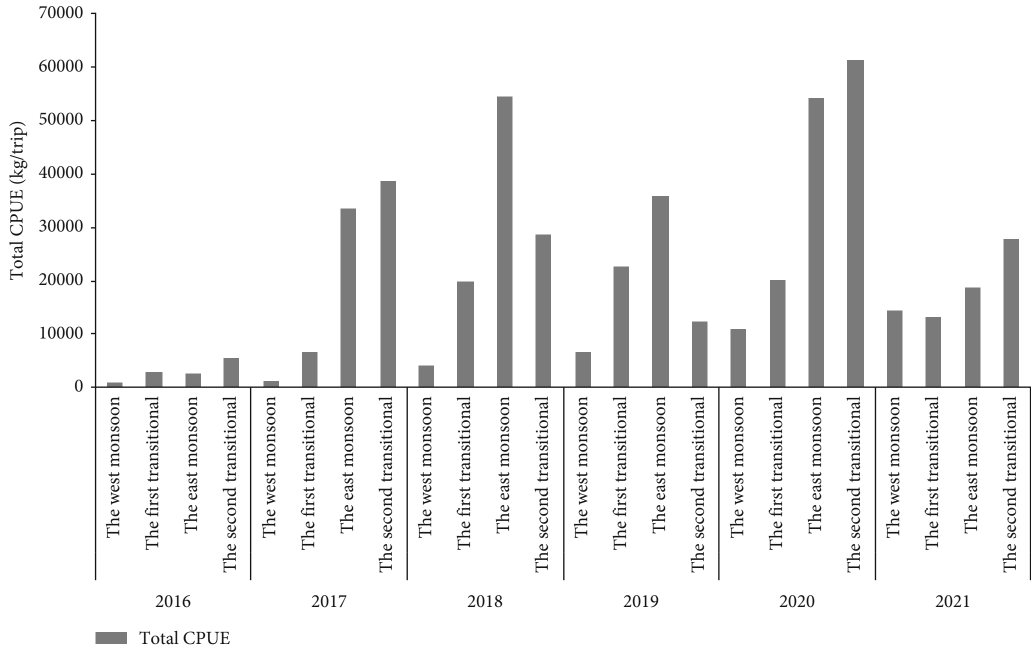

Figure 10: Seasonal CPUE of skipjack tuna during 2016-2021 in the South Java Sea.

can indicate upwelling and downwelling phenomena [35]. Therefore, SSH is an oceanographic parameter to determine potential fishing grounds [36].

The SSH average in the South Java Sea during 2016-2021 ranged from 0.268 to 0.639 m. The highest SSH average occurred during the Asian monsoon, while the lowest SSH average occurred during the Australian monsoon (see Figures 6 and 7). The low average of SSH during Australian Monsoon is caused by upwelling. Research [36] showed that upwelling in the South Java Sea occurred in June-October, while downwelling occurred in November-March. Research [37] stated that the SSH variations in Indonesian waters are affected by the monsoon wind. Based on Ekman's theory, upwelling causes a decrease in sea level, while downwelling causes an increase in sea level. SST and SSH trends had a direct proportional pattern (see Figures 2 and 6). High SST causes an increase in SSH because SST has a role in thermal expansion [38].

3.4. Sea Surface Salinity (SSS). Salinity is the total concentration of dissolved ions in one kilogram of water, expressed in practical salinity units (psu). Salinity concentration affects the osmoregulation mechanism of fish. Osmoregulation is a regulatory process carried out by living organisms to balance water and ions in the body with their environment. The average of SSS for each season during 2016-2021 at skipjack tuna fishing ground coordinates in the South Java Sea was calculated and graphed using Microsoft Excel, and it showed seasonal variations (see Figure 8).

The SSS average in the South Java Sea in 2016-2021 ranged from 33.075 to 34.514 psu. The highest SSS average occurred during the Australian monsoon, while the lowest average SSS occurred during the Asian monsoon (see Figures 8 and 9). The low salinity during the Asian monsoon was due to the high intensity of rainfall, which gave the seawater lots of fresh water. According to [39], the west monsoon winds that blow from the Asian to the Australian continent carry a lot of water vapor, making Indonesian waters experience high rainfall. Conversely, during the eastern monsoon, winds moving from the Australian to the Asian continent carry little water vapor. Moreover, the upwelling process or the rise of high-salinity water masses from deep layers to the surface layer also causes salinity in the upwelling area become high [28].

3.5. Catch per Unit Effort (CPUE). The CPUE analysis is aimed at determining the abundance of fish species and their utilization based on the division of catch (kg) with fishing effort (trip) [40]. Fishing gears used by skipjack tuna fishermen in the South Java Sea include hand line, long line, gill net, purse seine, troll line, and drift longline. The total CPUE of skipjack tuna in the South Java Sea during 2016-2021 had the lowest value of 880,295 kg/trip on December 2016-February 2017 (the west monsoon season) and the highest value of 61358,680 kg/trip on September-November 2020 (second transitional season). Generally, the highest CPUE total occurred during the Australian monsoon (east and second transitional seasons), while the lowest occurred during the Asian monsoon (west and first transitional seasons) (see Figure 10). Research by [41] also showed similar results; the highest CPUE value of skipjack tuna in the Indian Ocean occurred in June 2015 (the east monsoon season), while the lowest CPUE value occurred in February 2016 (the west monsoon season).

3.6. Generalized Additive Model Analysis. The results of GAM analysis for identifying the impact of oceanographic parameters on the CPUE of skipjack tuna are described in Table 2 and Figure 11. Based on the GAM statistical analysis results, it was concluded that model 15 was the best model.

Table 2: Generalized additive model results.

Model	Parameters	P value	AIC	CDE
1	SST	$<2e-16^{***}$	45571.08	3.51%
2	SSC	$<2e-16^{***}$	45619.14	2.24%
3	SSH	$<2e-16^{***}$	45590.86	3.01%
4	SSS	$<2e-16^{***}$	45622.72	1.93%
5	SST	$<2e-16^{***}$	45554.3	4.09%
	SSC	0.000291^{***}		
6	SST	$<2e-16^{***}$	45487.88	6.13%
	SSH	$<2e-16^{***}$		
7	SST	$<2e-16^{***}$	45553.73	4.15%
	SSS	0.00033^{***}		
8	SSC	$3.43e-06^{***}$	45559.54	4.2%
	SSH	$<2e-16^{***}$		
9	SSC	$<2e-16^{***}$	45585.74	3.27%
	SSS	$<2e-16^{***}$		
10	SSH	$<2e-16^{***}$	45439.3	7.43%
	SSS	$<2e-16^{***}$		
11	SST	$<2e-16^{***}$	45477.4	6.52%
	SSC	0.00276^{**}		
	SSH	$<2e-16^{***}$		
12	SST	$<2e-16^{***}$	45540.8	4.6%
	SSC	0.00117^{**}		
	SSS	0.00133^{**}		
13	SST	$<2e-16^{***}$	45360.85	9.72%
	SSH	$<2e-16^{***}$		
	SSS	$<2e-16^{***}$		
14	SSC	$1.82e-06^{***}$	45404.28	8.65%
	SSH	$<2e-16^{***}$		
	SSS	$<2e-16^{***}$		
15	SST	$<2e-16^{***}$	45357.92	10%
	SSC	0.0835		
	SSH	$<2e-16^{***}$		
	SSS	$<2e-16^{***}$		

Signif. codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 " " 1.

Model 15 consisted of SST, SSC, SSH, and SSS predictor variables with an AIC value of 45357.92, CDE value of 10%, and SST P value ($<2e-16^{***}$), SSC P value (0.0835), SSH P value ($<2e-16^{***}$), and SSS P value ($<2e-16^{***}$) less than 0.01 (see Table 2). Research by [42] about the relationship between oceanographic parameters and bigeye tuna in the Indian Ocean using GAM resulted in the best model from a combination of sea surface temperature, chlorophyll-a, and depth parameters. A study [43] conducted on skipjack tuna in the southwest Atlantic had the best GAM model composed of chlorophyll-a, salinity, thermocline depth, and sea surface temperature variables.

The results of the smoothing curve showed the optimal value of each oceanographic parameter as an indicator of skipjack tuna presence (see Figure 11). The optimal range of SST, SSC, SSH, and SSS values for skipjack tuna in the East Indian Ocean is 26-28°C, 0.07-0.5 mg/m^3, 0.4-0.5 m, and 34-34.5 psu. According to [41], the optimal sea surface temperature for skipjack tuna in the Indian Ocean was 27-29°C, with a chlorophyll-a optimum value of 0.21-0.26 mg/m^3. The SSH between 0.6 and 0.71 m was the most suitable value for skipjack tuna in the western and central Pacific Ocean [12]. In Maumere Bay, skipjack tuna were found at surface salinities of 32-35 psu [44].

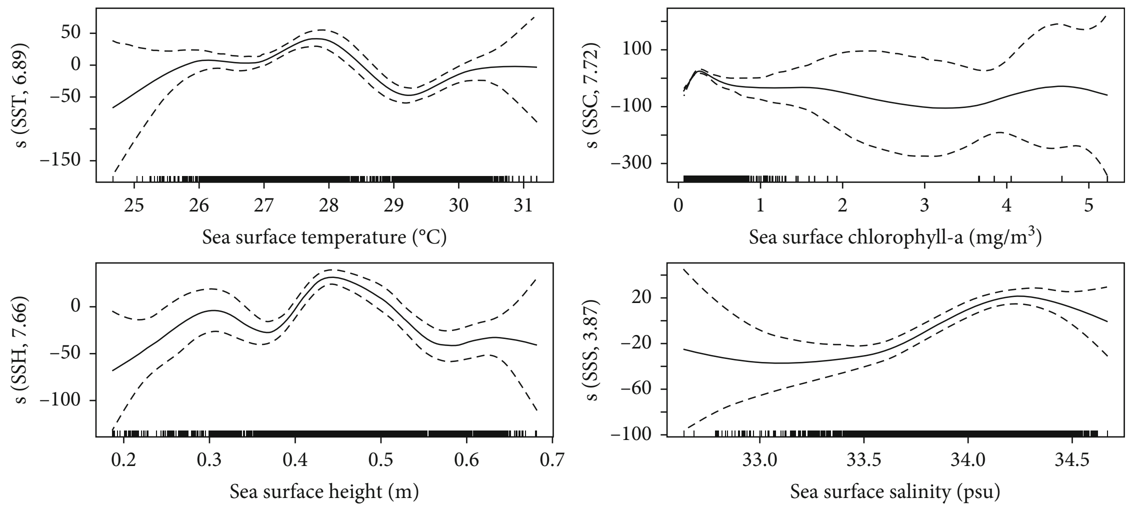

Figure 11: Smoothing curve generalized additive model.

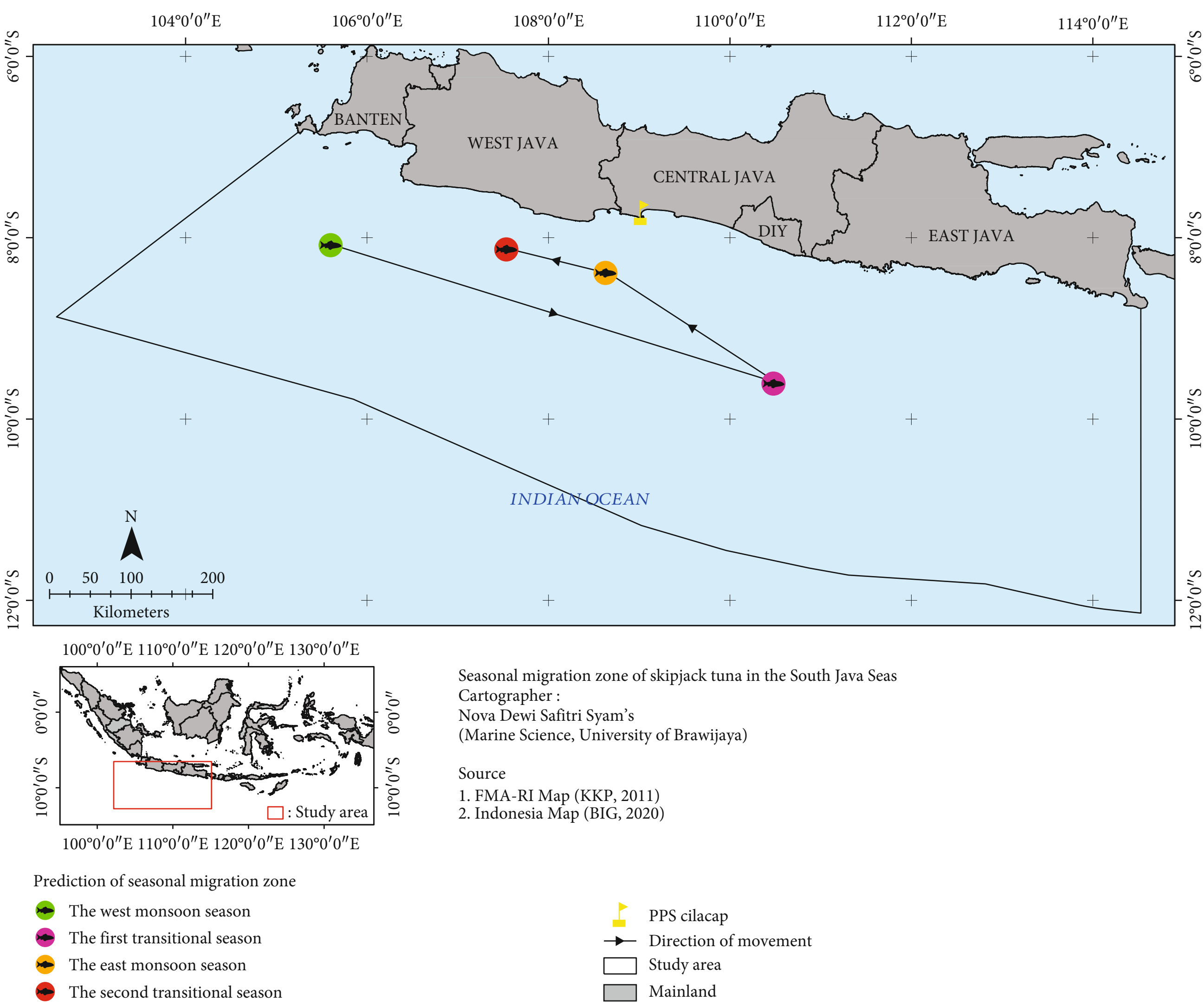

Figure 12: Map of seasonal migration zone of skipjack tuna in the South Java Sea.

3.7. Seasonal Migration Zone of Skipjack Tuna. The dynamics of oceanographic parameters caused skipjack tuna to migrate to find a habitat that suits their metabolism. The migration pattern of skipjack tuna in the South Java Sea varies seasonally (see Figure 12). In the west monsoon season (December-February), skipjack tuna is expected to cluster at 105° 35′, 54.524″ east and 8° 4′ 57.016″ south. Skipjack tuna furthermore tend to move southeast during the Asian monsoon. In the first transitional season (March-May), skipjack tuna is expected to cluster at 110° 28′ 49.477″ east and 9° 36′ 29.189″ south. The skipjack tuna movement is northwestward from the first transitional season to the east monsoon season (June-August). During the east monsoon season, skipjack tuna is expected to congregate at 108° 40′ 48.713″ east and 8° 23′ 15.451″ south. Skipjack tuna move northwest during the Australian monsoon. During the second transitional season (September-November), skipjack tuna is expected to congregate at 107° 32′ 9.583″ east and 8° 7′ 41.781″ south.

Skipjack tuna moved from western to southeast during the west monsoon season and first transitional season and tended to move northwest during the east monsoon season and second transitional season. This is similar to research [45] which stated that the movement of skipjack from July to October 2018 in the Makassar Strait was westward. The skipjack tuna is a type of tuna fish with a migration assisted by the current. Therefore, the migration pattern of skipjack tuna tends to follow currents [46].

4. Conclusions

The average values of oceanographic parameters at skipjack tuna fishing ground coordinates in the South Java Sea (2016-2021) are SST (26.050-30.816°C), SSC (0.094-0.564 mg/m^3), SSH (0.268-0.639 m), and SSS (33.075-34.514 psu). The best model from the GAM analysis is the combination of the four oceanographic parameters with an AIC value of 45357.92, a CDE value of 10%, and a P value of the four oceanographic parameters less than 0.01. Skipjack tuna in the South Java Sea migrates southeast during the Australian monsoon and tends to migrate northwest during the Asian monsoon.

Data Availability

The fishery data used to support the findings of this study were supplied by PPS Cilacap and PPP Pondokdadap under license and so cannot be made freely available. Requests for access to these data should be made to PPS Cilacap and PPP Pondokdadap office.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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