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The Use of statistical models in Identifying Skipjack Tuna Habitat Characteristics during the Southeast Monsoon in Bone Gulf, Indonesia

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Abstract. This study aimed to explore the relationship between the oceanographic factors with the distribution and abundance of skipjack tuna obtained by utilizing a pole and line in the Bone Gulf, Indonesia. The research was conducted during every southeast monsoon season (from April to September) from 2015 until 2018. Three oceanographic parameters were used in the process to understand this relationship, i.e., Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), and water depth. Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) that were used to predict the spatial pattern of the skipjack tuna showed that all considered parameters have a significant influence on the distribution of skipjack tuna in the study area. The fish are mostly distributed from coastal to offshore, ranging between 50 to 2,000 meters and even wider. The concentration tends to be high within the interval of 29.5 to 30.5 °C of SST and 0.25 to 0.35 mg m^{-3} of SSC, and 500 to 1,000 meters of water depth. The research has also found that the Skipjack tuna migration to Bone Gulf may have followed the current water interruption during the southeast monsoon. The fished prefer warmer temperatures and lower primary productivities waters in the offshore areas. These preferred conditions may represent the optimal habitat of the skipjack tuna in the Bone Gulf during the southeast monsoon periods.

Key words: oceanographic factors, pole and line, skipjack tuna, statistical models.

Abbreviations (if any): Sea Surface Temperature (SST), Sea Surface Chlorophyll-*a* (SSC), Catch Per Unit Effort (CPUE), generalized Additive Models (GAMs), Generalized Linear Models (GLMs), Akaike Information Criterion (AIC), Cumulative Deviance Explained (CDE)

Running title: Statistical Model for Skipjack Habitat

INTRODUCTION

Skipjack tuna (*Katsuwonus pelamis*) is the most crucial targeting by marine fisheries in the world's oceans (Galland et al. 2016). Large schools of adult skipjack tuna are often associated with juvenile yellowfin (*Thunnus albacores*) and bigeye tuna (*Thunnus obesus*) (IOTC 2020). Skipjack tuna is a highly migratory pelagic species inhabiting all tropical and subtropical waters (Artetxe-Arrate et al. 2020). However, they are found mainly in the tropical areas of the Atlantic, Indian and Pacific Oceans, with the most incredible abundance seen near the equator. Since juvenile yellowfin and bigeye tuna often school with adult skipjack tuna, they are caught by purse seine and pole and line vessels that the main target is skipjack tuna (Hidayat et al. 2019; IOTC 2019; Safruddin et al. 2020).

The dynamic of oceanographic factors could change the natural fluctuations of the skipjack tuna in distribution and abundance in the coastal and offshore areas (Mugo et al. 2010; Tseng et al. 2010; Wang et al. 2016). The distribution can also influence if the small pelagic fish such anchovy is abundant in the same area (Safruddin et al. 2018). Therefore, information is rapidly needed on the effects of oceanography factors related to skipjack tuna distribution (Andrade and Garcia, 1999). This information is needed to predict fishing ground potential zones for sustainable skipjack tuna fishery in the study area.

Statistical models such as generalized additive models (GAMs) and generalized linear models (GLMs) as a method can be one of the most useful for determining the fish distribution in relation to oceanography factors such as sea surface temperature (SST), sea surface chlorophyll-a (SSC), and water depth (Safruddin 2013; Safruddin et al. 2018; Selao et al. 2019).

The Gulf of Bone is one of the best skipjack tuna habitats in Indonesian waters, with the peak fishing season lasting from early April until the end of September (southeast monsoon). Although skipjack tuna is an iconic species in Bone Gulf, local availability of skipjack tuna is a key economy for pole and line fishery. However, a lack of information about this tuna distribution spatially and temporally. As a result, this study offers the chance to investigate skipjack tuna under various oceanographic conditions connected to the use of pole and line fishing gear and discuss the oceanography elements impacting skipjack tuna distribution and apply statistical models.

MATERIALS AND METHODS

Study area

The study area was located in Bone Gulf (3 - 5°S) and (120 - 122°E), South Sulawesi, Indonesia (Figure 1). The field surveys used a pole and line (local commercial fisheries) to investigate the fishing ground positions and the number of skipjack tuna catches during the study. Oceanography observations (satellite imagery data) were conducted monthly during the southeast monsoon (in April to September) from 2015 until 2018, respectively.

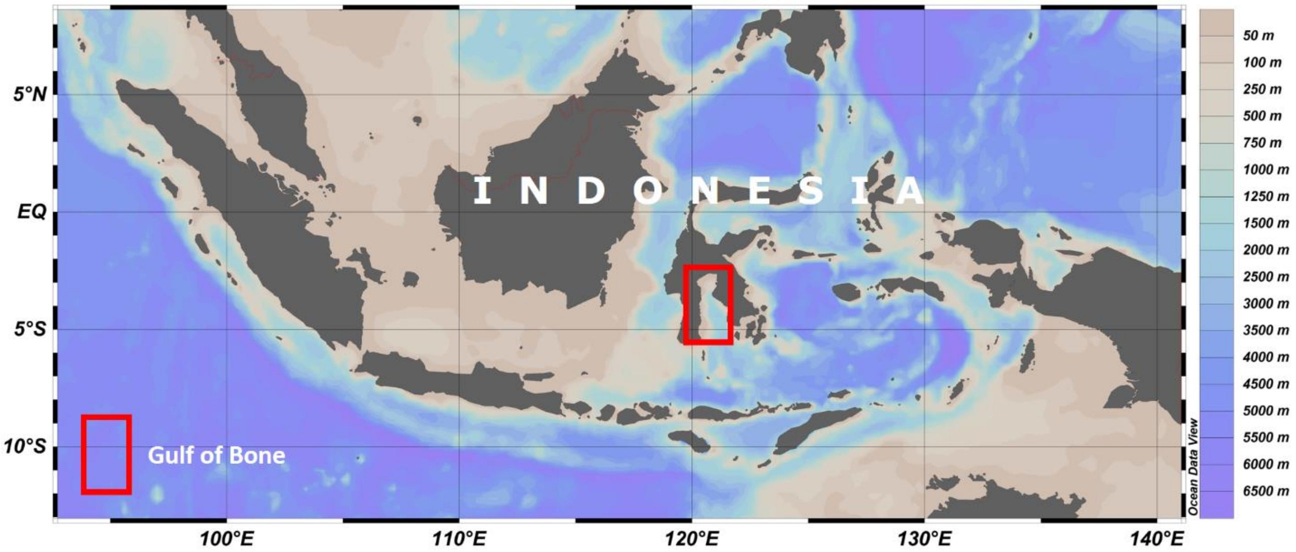

Figure 1. Map of Indonesia Seas with the Red Box was representing the study area.

Procedures

Data Collection

In-situ data were obtained through the scientific survey, the fishing base at Murante fish landing site, Luwu district. We were gathered the fishery data from 508 fishing ground positions. A global positioning system (GPS) was used to determine fishing grounds coordinates (latitude and longitude). The In-situ field data consisted of fishing position and catch per unit efforts (CPUEs). The oceanographic images data (SST, SSC, and depth) were obtained from satellite oceanography imaginary data of high-resolution Moderate-Resolution Imaging Spectroradiometer (MODIS) aqua with a spatial resolution of 4 km April to September 2015 until 2018. The waters depth data was gained from the ETOPO2 satellite database. In this study, we used monthly temporal resolution. Furthermore, the SST and SSC averaged during southeast monsoon were mapped as shown in Figures 2 and 3.

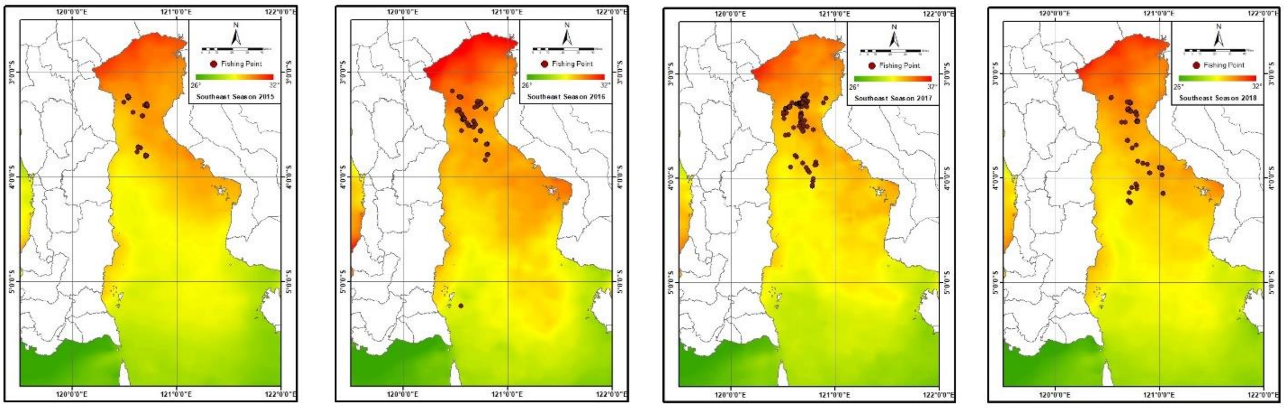

Figure 2. The Profiles of SST average during southeast monsoon in 2015 until 2018 overlaid with the skipjack tuna distribution in Bone Gulf waters.

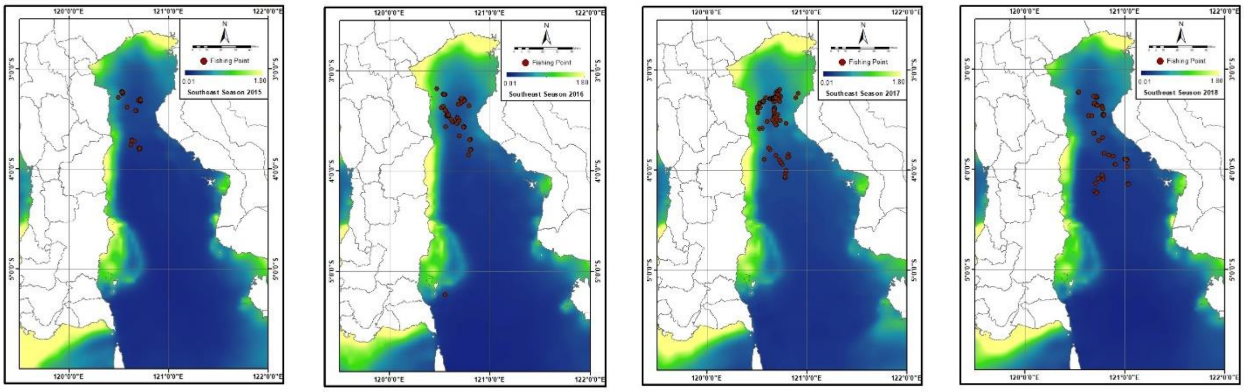

Figure 3. The Profiles of SSC average during southeast monsoon in 2015 - 2018 overlaid with the skipjack tuna distribution in Bone Gulf waters.

Data analysis

Determining the effect of oceanographic parameters on horizontal distributions of skipjack tuna in the sea, statistical models (Hastie and Tibshirani 1990) are used for the CPUE and oceanographic datasets. The models, such as GAMs and GLMs, were created using the mgcv package in R-studio (Wood 2006) to predict the spatial patterns of skipjack tuna. The response variable used skipjack tuna catches (CPUE/fishing trip), and the predictor used oceanographic parameters (SST, SSC, and depth).

So the hypothesized interactions between oceanographic parameters and skipjack tuna are most likely non-linear, GAM was employed as an experimental technique to determine the forms of the associations. The connections between the skipjack distribution and each predictor (SST, SSC, and depth) were also determined. In a GLM, the proper functions were utilized to identify these forms in the linear model, as indicated in Equations (1) and (2) (Safruddin 2013).

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (SSC) + s3\ (depth) + \varepsilon \quad \text{(GAM model)} \qquad (1)$$

$$g(\mu i) = \beta 0 + \beta 1\ (SST) + \beta 2\ (SSC) + \beta 3\ (depth) + \varepsilon \quad \text{(GLM model)} \qquad (2)$$

where g is link function, μi is the expected value of the dependent variable for the presence of skipjack tuna (CPUE), α and $\beta 0$ are the models constant, sn is the predictor variables smoothing function, and ε is a random error term, and βn is the vector of model coefficients.

The Gaussian family with identical link functions was chosen since the skipjack tuna CPUE has a continuous distribution. Models were created from the ground up, with only one independent component, such as SST, and predictor components added later. Model selection was influenced by the predictor's significance, Akaike Information Criterion (AIC) reduction, and the deviance explained value. The best model was chosen from a group of seven to build the GAMs/GLMs. The GAMs/GLMs model was utilized to compare the results of the prediction models using a statistical criterion. They were also used to explain all observations with multiple variables, including inter-variable correlations (Safruddin 2013).

RESULTS AND DISCUSSION

Skipjack Tuna Fishing Ground

Skipjack tuna fishing grounds were mapped on latitude and longitude scales, with SST, SSC, and depth overlay (Figures 2 - 4). CPUE marks the position along the railway in Figures 2 - 4, and each school is designated as a single point. Map contours with high SST, SSC, and depth, or the opposite, were also discovered.

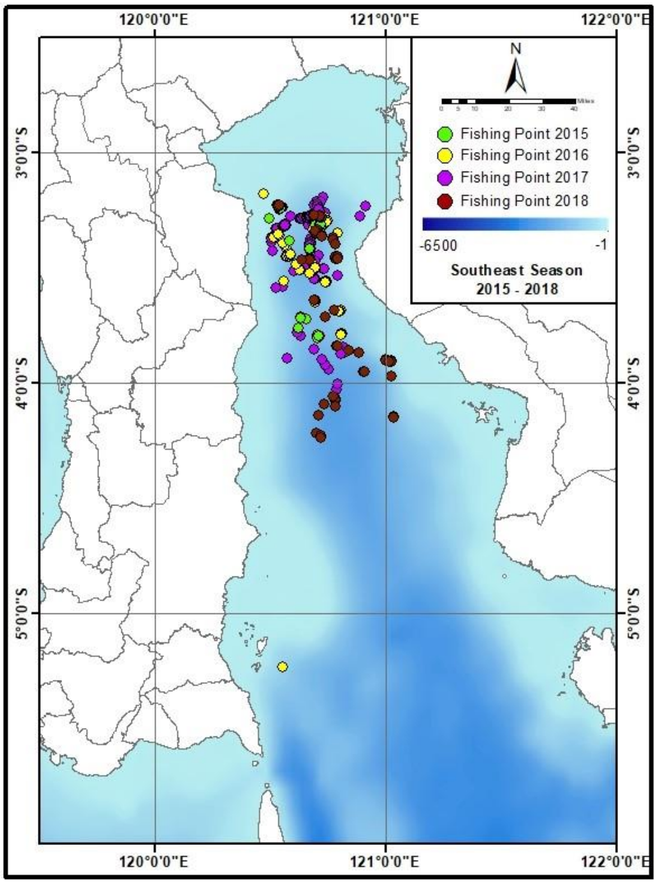

Figure 4. The profiles of bathymetric overlain with the skipjack tuna distribution during southeast monsoon in 2015 - 2018 in Bone Gulf waters.

The lowest SST and the highest SSC for the southeast monsoon occur every year. On the otherwise, in the northwest season. Skipjack tuna was the least abundant in the lower SST area (Figure 3) due to changes in water temperature caused by water currents from the Flores Sea entrance to Bone Gulf. So it may be a strategy in biological processes under changing oceanographic conditions related to fish growth. Skipjack tuna stock is positively correlated with oceanographic factors. Skipjack tuna is distributed mainly in nearshore areas in the water depth range of 50 to 2,000 m (Figure 4). The horizontal profiles of the SST and SSC structures for the 2015-2018 southeast season, respectively (Figures 2 and 3), are warmer near the coast than offshore. Skipjack schools occupy areas in the offshore area where they prefer relatively warm SST and lower SSC (Figures 2 and 3).

The environmental conditions of skipjack tuna fishing grounds were used for four monthly datasets (April – August). As a result, the preference range suggested a possible association between all of the factors examined. For example, figure 4 shows that skipjack tuna were found in temperatures ranging from 29.5 to 31.05 °C. On the otherwise, the skipjack tuna schools concentrated in the narrow ranges of 0.15-1.00 mg m^{-3} regarding SSC.

Effects of oceanographic factors on skipjack tuna distribution

The oceanographic condition of the skipjack tuna schooling coordinate was employed in the current study for displaying the area and further analysis. Tables 1 and 2 show the models built using GAMs/GLMs on the skipjack tuna distribution scenarios utilizing predictor parameters (SST, SSC, and depth).

Tables 1 and 2 present the results for each of the seven GAM and GLM models. Each model's predictor component (s) significantly affected the skipjack tuna distribution in $p < 0.05$ reference levels, except depth as two and three predictors (Table 1). However, only SST substantially contributed to a single model predictor, two model predictors, and three model predictors in GLMs (Table 2). For the final model combination of SST, SSC, and depth, the cumulative deviance explained (CDE) was 21.9% (GAMs) and 12.830% (GLMs), respectively. Thus, tables 1 and 2 suggest that the influence of oceanographic conditions may explain the fluctuation of skipjack tuna abundance distribution. Additionally, GAMs with the highest CDE were well-suited to characterize the influence of oceanographic conditions on skipjack tuna distribution and abundance.

Tables 1 and 2 show the results of GAMs and GLMs, respectively. For both statistical models, the SST had the largest deviance explained among the single variable models. According to AIC (6048.045) and CDE (21.9%) and as the best model predictor of GAM, the combination of SST and SSC predicted relatively more significant variability in skipjack tuna catches. The AIC values for the three-parameter models were low (6049.831), and the most significant deviation was explained (21.9%). SST was the sole predictor model with the lowest AIC (6083.072) and the maximum CDE among GLMs model (12.870%) and was also found in combining two-parameter models between SST and SSC. The three parameter models had the lowest AIC and the highest CDE overall (12.830 %). All of the results produced by combining predictor factors at various levels revealed an increase or decrease in CDE and a higher AIC value of variation.

GAMs models were more effective than GLMs in understanding the effect of oceanographic factors on skipjack tuna distribution and abundance, as shown in Tables 1 and 2. The result of the GAM plots give impacts of each predictor on schooling density of skipjack tuna are shown in Figures 5 and 6. The observed data points are represented by the rug plot on the horizontal axis, while the think line shows the fitted function, and the grey shading represents the 95 percent confidence interval (Safruddin 2013).

Table 1. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GAMs Models. Also included are the significant factor, AIC value and CDE.

No.	Model	Oceanographic factor	P-*value*	AIC	CDE (%)
1.	**SST**	SST	<2e-16 ***	6054.183	20.400
2.	**SSC**	SSC	2.22e-06 ***	6121.052	8.400
3.	**Depth**	Depth	0.000109 ***	6132.647	4.970
4.	**SST + SSC**	SST	2.46e-15 ***	6048.045	21.900
		SSC	0.000293 ***		
5.	**SST + Depth**	SST	2.12e-14 ***	6067.725	17.300
		Depth	0.296		
6.	**SSC + Depth**	SSC	0.000899 ***	6121.672	8.350
		Depth	0.236307		
7.	**SST + SSC + Depth**	SST	2.44e-15 ***	6049.831	21.900
		SSC	0.000289 ***		
		Depth	0.832189		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Figure 5 describes the impact of oceanographic conditions on skipjack tuna distribution. Around 29.5 – 30.5 °C, the SST (Figure 5a) had a noticeable positive effect on skipjack tuna distribution. The confidence intervals are broader because there are fewer data points at 30.5 - 31.0 °C. In the SSC plot (Figure 5b), there was a beneficial influence on school distribution in the SSC ranges of 0.25 - 0.35 mg m^{-3}. A consistent influence on skipjack tuna distribution of 50 - 2,000 m was seen for depth (Figure 5c). The study also found that models combining SST and SSC produced the most significant model prediction, with the lowest AIC and highest CDE (Figure 5d). Skipjack tuna distribution in the Northern Pacific Ocean near Japan waters had SST and SSC optimal temperatures of 20.5 - 26 °C and 0.3 - 0.37 mg m^{-3}, respectively, according to Mugo (2010). The findings of this study corroborated those of Zainuddin et al. (2017), who discovered that distribution of skipjack tuna in the coastal area was primarily around 50 m depth.

Table 2. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GLMs Models. Also included are the significant factor, AIC value and CDE.

No.	Model	Oceanographic factor	P-*value*	AIC	CDE (%)
1	**SST**	SST	<2e-16 ***	6083.072	12.960
2	**SSC**	SSC	0.89413	6154.549	0.194
3	**Depth**	Depth	0.17566	6152.724	0.165
4	**SST + SSC**	SST	<2e-16 ***	6084.600	12.870
		SSC	0.494		
5	**SST + Depth**	SST	<2e-16 ***	6084.987	12.800
		Depth	0.772		
6	**SSC + Depth**	SSC	0.385	6153.966	0.117
		Depth	0.109		
7	**SST + SSC + Depth**	SST	<2e-16***	6085.819	12.830
		SSC	0.282		
		Depth	0.379		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

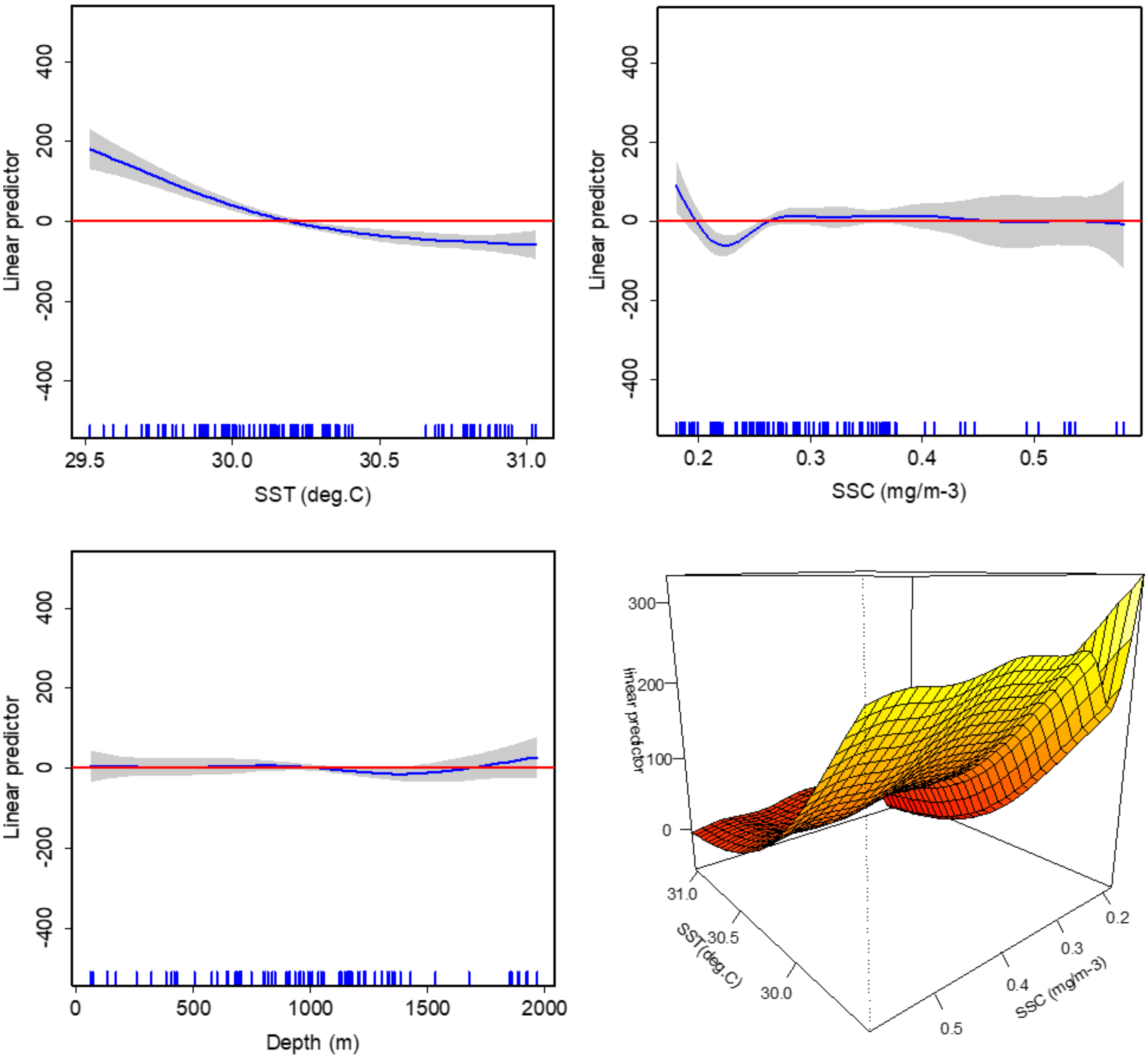

Figure 4. Skipjack tuna distribution responses of oceanographic factors; (a) SST, (b) SSC, (c) depth, and (d) best model predictor.

Discussion

Oceanographic circumstances such as SST, which have the most significant impact on growth stages of fish and distribution (Yuniarti et al. 2013; Syah et al. 2020), the main role in the natural oscillations of skipjack tuna stocks. As a result, SST is a great indicator for the fishing ground of skipjack tuna to have been used by fishermen and investigators for decades. Furthermore, changes in oceanic (physical and biological) parameters may significantly impact migration patterns and fish growth (Safruddin et al. 2018).

Because the SST in the research region may vary, measurements should be obtained frequently. More samples may be required to accomplish this goal. Therefore, one of this research objective about how oceanographic data will be used in research (e.g., correlation with skipjack tuna distribution and abundance). Temperature fluctuations are often linked to the biological richness (Iskandar et al. 2017; Takarina et al. 2018), such as anchovy distribution and abundance as prey for skipjack tuna, and they have an important influence on fish physiology (Kunarso et al. 2011; Olson et al. 2016; Duffy et al. 2017).

Satellite remote sensing imagery directly indicates horizontal and large-area information on oceanographic conditions, which may be utilized to understand oceanographic processes in the surface water better. The combination of satellite data with acoustic technology will, of course, increase the accuracy of the data. For example, they combine CTD and satellite data when conducting data observations (Safruddin 2013). As a result, four-year datasets of oceanographic conditions (SST, SSC, and water depth) on skipjack tuna position were employed, with scatter plots and optimal ranges indicating a possible association among all variables observed as shown in Figure 5.

Skipjack tuna can be found in coastal areas, where it can sometimes be found in great numbers, particularly in upwelling areas (Sari et al. 2018; Wijaya et al. 2020). The study detailed the interaction between skipjack tuna and their oceanographic variable at the aspect of temporal and spatial scales to comprehend the numerous processes involved and how they might be utilized to model their dynamics and forecast their abundance (Prista et al. 2011; Selvaraj et al. 2020).

Oceanographic conditions are essential variables to assess the abundance of fish in the waters, especially skipjack tuna, representing the original habitats. The distribution of skipjack tuna observed during the daytime is closely related to the dynamics of oceanographic variables and fishing operations in Bone Gulf. As shown in Tables 1 and 2 and Figure 5, the effect of oceanographic parameters on the abundance and distribution of skipjack tuna for water depths is also a reference. The p-value, AIC, and CDE can all be used to assess the impact of changing oceanographic conditions on skipjack tuna CPUE. As a result, oceanographic variables connected to skipjack tuna distribution are critical to understanding skipjack tuna habitat preferences.

Oceanographic phenomena in the waters such as frontal oceanic zones, eddies, and upwelling area often occur make different characteristics like in the Bone Gulf and the Flores Sea (Zainuddin et al. 2017, 2019; Hidayat and Zainuddin 2018; Hidayat et al. 2019b). This event makes the waters very dynamic and affects the horizontal distribution of fish in the Bone Gulf. The dynamic oceanographic parameters in this area produce highly productive habitats and serve as foraging grounds for various commercially and ecologically important species such as anchovies and skipjack tuna (Safruddin et al 2018; Hidayat et al 2019b)

The results of this study indicate that the SST tolerance value for skipjack tuna is in the range of 29.5 to 30.5 °C and for SSC parameters in the range of 0.25 – 0.35 mg m^{-3} (Figures 5a and 5b). however, in addition to SST and SSC, Indonesian throughflow (ITF) and Asian monsoons also influence the location of the optimum habitat for skipjack tuna (Gordon 2005). changes in the value of SST in the waters are heavily influenced by the seasonal cycle, in contrast to the SSC, which is not much influenced by the seasonal cycle. Therefore, the migration of skipjack tuna in the northern waters of Bone Gulf is thought to have followed the mass movement of water in the southeast monsoon by occupying relatively warm areas in offshore waters.

Based on the lowest AIC value and the highest CDE, the GAM nonlinear model is the best statistical model to understand the effect of oceanographic parameters on the distribution and abundance of skipjack tuna. This study is also supported by previous findings in the Makassar Strait, which reported that the GAM model effectively assessed the effect of oceanographic parameters on skipjack tuna (Hidayat et al. 2019a) and small pelagic fish such as anchovies in Bone Gulf (Safruddin et al. 2018).

This study concludes that the GAM statistical model has succeeded in explaining the effect of oceanographic parameter conditions on the distribution of skipjack tuna in Bone Gulf. This study also shows the vital role of oceanographic parameters in understanding the habitat of skipjack tuna related to its abundance and distribution in the waters. The distribution of skipjack tuna in the ocean shows a strong relationship with several parameters such as SST, SSC, and water depth. Suitable or optimal conditions for skipjack tuna represent skipjack fishing areas during the study in the southeast monsoon period. Oceanographic parameters associated with fish catches correspond to the spatial and temporal distribution of skipjack tuna and have become a hot topic of discussion worldwide (Andrade 2003; Mugo et al. 2010; Zainuddin et al. 2019). From the results of this study, it can be suggested that management decisions to increase fishery yields need to consider oceanographic conditions and characteristics in the waters.

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[biodiv] Submission Acknowledgement

1 message

Ahmad Dwi Setyawan <smujo.id@gmail.com> Thu, Dec 2, 2021 at 10:42 AM
To: Safruddin Hasyim <safruddin@fisheries.unhas.ac.id>

Safruddin Hasyim:

Thank you for submitting the manuscript, "The Use of statistical models in Identifying Skipjack Tuna Habitat Characteristics during the Southeast Monsoon in Bone Gulf, Indonesia " to Biodiversitas Journal of Biological Diversity. With the online journal management system that we are using, you will be able to track its progress through the editorial process by logging in to the journal web site:

Submission URL: https://smujo.id/biodiv/authorDashboard/submission/10023
Username: safruddin_75

If you have any questions, please contact me. Thank you for considering this journal as a venue for your work.

Ahmad Dwi Setyawan

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[biodiv] Editor Decision

1 message

Ayu Astuti <smujo.id@gmail.com> Wed, Mar 23, 2022 at 7:29 PM
To: Safruddin Hasyim <safruddin@fisheries.unhas.ac.id>, Rachmat Hidayat <rh191993@gmail.com>, St Aisjah Farhum <icha_erick@yahoo.com>, Mukti Zainuddin <muktizunhas@gmail.com>

Safruddin Hasyim, Rachmat Hidayat, St Aisjah Farhum, Mukti Zainuddin:

We have reached a decision regarding your submission to Biodiversitas Journal of Biological Diversity, "The Use of statistical models in Identifying Skipjack Tuna Habitat Characteristics during the Southeast Monsoon in Bone Gulf, Indonesia ".

Our decision is: Revisions Required

Reviewer A:

Dear Authors,

Thank you for submitting this interesting paper to Biodiversitas. The paper describes the use of models to identify locations for skipjack tuna fishing. The paper has some potential value to those involved in fisheries. Overall, I found the manuscript to be well formatted, with a clear message and repeatable methods. The results are well organised (but see comments on the word manuscript), and the outcomes are clear in the discussion. There are a few relatively small revisions required; details can be found on the manuscript. On the whole, an interesting and well designed study.

Recommendation: Revisions Required

Biodiversitas Journal of Biological Diversity

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The use of statistical models in identifying skipjack tuna habitat characteristics during the Southeast Monsoon in the Bone Gulf, Indonesia

Manuscript received: 02 12 2021. Revision accepted: .... 2022.

Abstract. This study aimed to explore the relationship between the oceanographic factors and the distribution and abundance of skipjack tuna obtained by pole and line fishing in the Bone Gulf, Indonesia. The research was conducted during the southeast monsoon season (April–September) from 2015 until 2018. Three oceanographic parameters were used to understand this relationship, i.e., Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), and water depth. Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) used to predict the spatial pattern of the skipjack tuna showed that all considered parameters significantly influenced the distribution of skipjack tuna in the study area. The fish are mostly distributed from coastal to offshore areas, ranging between 50 to 2,000 meters and even wider. The concentration tends to be high within the range of 29.5 to 30.5°C of SST, 0.25 to 0.35 mgm^{-3} of SSC, and 500 to 1,000 meters of water depth. The research also found that the skipjack tuna migration to the Bone Gulf may have followed the current water interruption during the southeast monsoon, for preferred warmer temperatures and lower primary productivity waters in the offshore areas. This may represent the optimal habitat of the skipjack tuna during this period.

Keywords: oceanographic factors, pole and line, skipjack tuna, statistical models.

Abbreviations: Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), Catch Per Unit Effort (CPUE), Generalized Additive Models (GAMs), Generalized Linear Models (GLMs), Akaike Information Criterion (AIC), Cumulative Deviance Explained (CDE)

Running title: Statistical Model for Skipjack Habitat

INTRODUCTION

Skipjack tuna (*Katsuwonus pelamis*) is the most crucial target catch of marine fisheries in the world's oceans (Galland et al. 2016). Large schools of adult skipjack tuna are often associated with juvenile yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (IOTC 2020). Skipjack tuna is a highly migratory pelagic species inhabiting all tropical and subtropical waters (Artetxe-Arrate et al. 2020). However, they are found mainly in the tropical areas of the Atlantic, Indian, and Pacific Oceans, with the most incredible abundance seen near the equator. Since juvenile yellowfin and bigeye tuna often school with adult skipjack tuna, they are caught by purse seine and pole and line vessels whose main target is skipjack tuna (Hidayat et al. 2019; IOTC 2019; Safruddin et al. 2020).

The dynamics of oceanographic factors could affect the natural fluctuations in the distribution and abundance of skipjack tuna in the coastal and offshore areas (Mugo et al. 2010; Tseng et al. 2010; Wang et al. 2016). The distribution could also be influenced by the abundance of small pelagic fish such as anchovy in the same area (Safruddin et al. 2018). Therefore, there is an urgent need for information on the effects of oceanographic factors on skipjack tuna distribution (Andrade and Garcia 1999) to predict fishing ground potential zones for sustainable skipjack tuna fishery in the study area.

Statistical models such as generalized additive models (GAMs) and generalized linear models (GLMs) can be the most useful methods for determining the fish distribution in relation to oceanographic factors such as the sea surface temperature (SST), sea surface chlorophyll-a (SSC), and water depth (Safruddin 2013; Safruddin et al. 2018; Selao et al. 2019).

The Bone Gulf is one of the best skipjack tuna habitats in Indonesian waters, with the peak fishing season lasting from early April until the end of September (southeast monsoon). Although skipjack tuna is an iconic species in the Bone Gulf, its local availability is a key factor for the pole and line fishery economy. However, there is a lack of information about its distribution, both spatially and temporally. Hence, this study is an attempt to investigate the availability of skipjack tuna caught using pole and line fishing gear under various oceanographic conditions and to discuss the oceanographic elements impacting skipjack tuna distribution by applying statistical models.

MATERIALS AND METHODS

Study area

The study area was located in the Bone Gulf (3–5°S) and (120–122°E), South Sulawesi, Indonesia (Figure 1). The field surveys used the pole and line method (local commercial fisheries) to investigate the fishing ground positions and the number of skipjack tuna catches during the study. Oceanography observations (satellite imagery data) were conducted monthly during the southeast monsoon (April–September) from 2015 until 2018.

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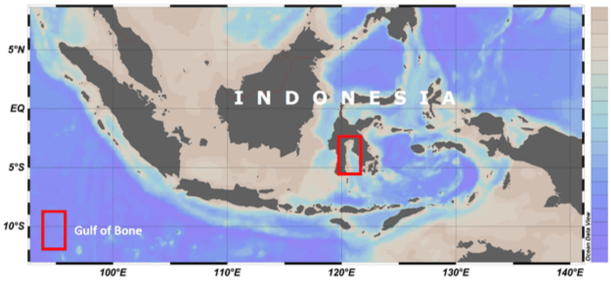

Figure 1. Map of the Indonesian seas with the red box representing the study area.

Procedures

Data Collection

In-situ data were obtained through a scientific survey at the fishing base at Murante fish landing site, Luwu district. We gathered the fishery data from 508 fishing ground positions. A global positioning system (GPS) was used to determine fishing ground coordinates (latitude and longitude). The in-situ field data consisted of the fishing position and catch per unit efforts (CPUEs). The oceanographic parameters (SST, and SSC) were obtained from satellite oceanography imagery data of high-resolution Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS), with a spatial resolution of 4 km, from 2015 until 2018 (April–September). The water depth data was gained from the ETOPO1 satellite database. In this study, we used monthly temporal resolution. Furthermore, the SST and SSC averaged during southeast monsoon were mapped as shown in Figures 2 and 3, respectively.

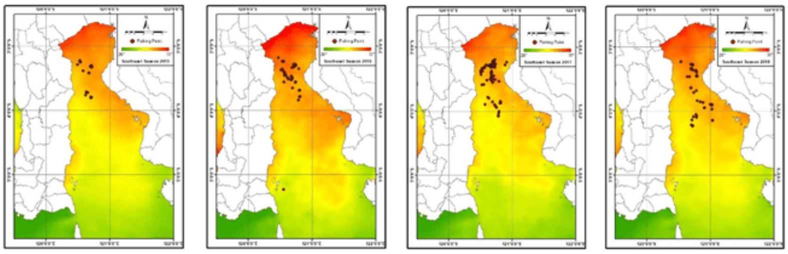

Figure 2. The profiles of SST average during southeast monsoon from 2015 until 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters.

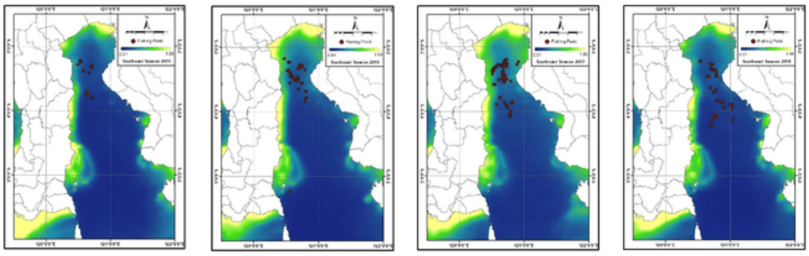

Figure 3. The profiles of SSC average during southeast monsoon from 2015 to 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters.

Data Analysis

To determine the effect of oceanographic parameters on horizontal distributions of skipjack tuna in the sea, statistical models (Hastie and Tibshirani 1990) were used for the CPUE and oceanographic datasets. The models, such as GAMs and GLMs, were created using the MGCV package in R-studio (Wood 2006) to predict the spatial patterns of skipjack tuna. The response variable used skipjack tuna catches (CPUE/fishing trip), and the predictor used oceanographic parameters (SST, SSC, and depth).

The hypothesized interactions between oceanographic parameters and skipjack tuna distribution are most likely non-linear. GAM was employed as an experimental technique to determine the forms of the associations. The connections between the skipjack distribution and each predictor (SST, SSC, and depth) were also determined. In a GLM, proper functions were utilized to identify these forms in the linear model, as indicated in Equations (1) and (2) (Safruddin 2013).

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (SSC) + s3\ (depth) + \varepsilon \quad \text{(GAM model)} \qquad (1)$$

$$g(\mu i) = \beta 0 + \beta 1\ (SST) + \beta 2\ (SSC) + \beta 3\ (depth) + \varepsilon \quad \text{(GLM model)} \qquad (2)$$

where g is the link function, μi is the expected value of the dependent variable for the presence of skipjack tuna (CPUE), α0 and β0 are the respective model's constant, sn is the predictor variable's smoothing function, ε is a random error term, and βn is the vector of model coefficients.

The Gaussian family with identical link functions was chosen since the skipjack tuna CPUE has a continuous distribution. Models were created from the ground up, with only one independent component such as SST, and predictor components were added later. Model selection was influenced by the predictor's significance, Akaike Information Criterion (AIC) reduction, and the deviance explained value. The best model was chosen from a group of seven to build the GAMs/GLMs. The GAMs/GLMs model was utilized to compare the results of the prediction models using a statistical criterion. They were also used to explain all observations with multiple variables, including inter-variable correlations (Safruddin 2013).

RESULTS AND DISCUSSION

Skipjack tuna fishing ground

Skipjack tuna fishing grounds were mapped on latitude and longitude scales, with SST, SSC, and depth overlay (Figures 2–4). CPUE marks the position along the overlay in Figures 2–4, and each school is designated as a single point. Map contours with high SST, SSC, and depth, or the opposite, were also discovered.

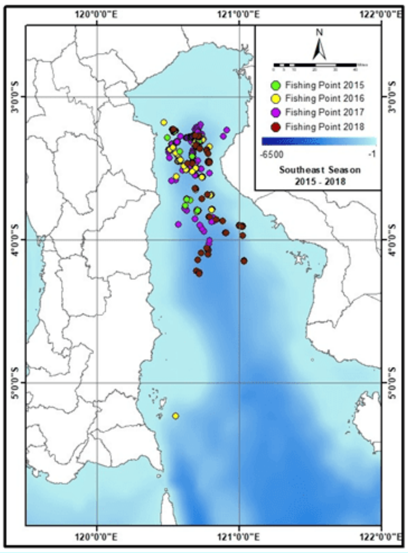

Figure 4. The profiles of bathymetric overlay with the skipjack tuna distribution during southeast monsoon from 2015 to 2018 in the Bone Gulf waters.

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The lowest SST and the highest SSC occur every year during the southeast monsoon period. The reverse happens in the northwest monsoon season, skipjack tuna was least abundant in the lower SST area (Figure 2) due to changes in water temperature caused by water currents from the Flores Sea entrance to the Bone Gulf. This could be a strategy in biological processes related to fish growth under changing oceanographic conditions. Skipjack tuna stock is positively correlated with oceanographic factors. It is distributed mainly in nearshore areas in the water depth range of 50 to 2,000 m (Figure 4). The horizontal profiles of the SST and SSC structures for the 2015–2018 southeast monsoon season (Figures 2 and 3) are warmer near the coast than offshore. Skipjack schools occupy offshore areas where they prefer relatively higher SST and lower SSC (Figures 2 and 3).

The environmental conditions of skipjack tuna fishing grounds were used for four monthly datasets (April–August). As a result, the preference range suggested a possible association between all examined factors. For example, Figure 4 shows that skipjack tuna were found in temperatures ranging from 29.5 to 31.05°C. Likewise, the skipjack tuna schools concentrated in the narrow ranges of 0.15–1.00 mgm^{-3} with respect to SSC.

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Effects of oceanographic factors on skipjack tuna distribution

The oceanographic conditions of the skipjack tuna schooling coordinates were employed in the current study for displaying the area and further analysis. Tables 1 and 2 show the models built using GAMs/GLMs on the skipjack tuna distribution scenarios utilizing predictor parameters (SST, SSC, and depth).

Tables 1 and 2 present the results for each of the seven GAM and GLM models. Each model's predictor component(s) significantly affected the skipjack tuna distribution in $p < 0.05$ reference levels, except depth as predictor two and three (Table 1). However, only SST substantially contributed to a single model predictor, two model predictors, and three model predictors in GLMs (Table 2). For the final model combination of SST, SSC, and depth, the cumulative deviance explained (CDE) was 21.9% (GAMs) and 12.830% (GLMs), respectively. Thus, Tables 1 and 2 suggest that the influence of oceanographic conditions may explain the fluctuation of skipjack tuna abundance distribution. Additionally, GAMs with higher CDE were well-suited to characterize the influence of oceanographic conditions on skipjack tuna distribution and abundance.

Tables 1 and 2 show the results of GAMs and GLMs, respectively. For both statistical models, the SST had the largest deviance explained among the single variable models. According to AIC (6048.045) and CDE (21.9%), and as the best model predictor of GAM, the combination of SST and SSC predicted relatively more significant variability in skipjack tuna catches. The AIC values for the three-parameter models were low (6049.831) and the most significant deviation explained was 21.9%. SST was the sole predictor model with the lowest AIC (6083.072) and the maximum CDE on the GLMs model (12.870%) and was also found as a combined two-parameter model between SST and SSC. The three-parameter models had the lowest AIC and the highest CDE overall (12.830%). All results produced by combining predictor factors at various levels revealed an increase or decrease in CDE and a higher AIC value of variation.

GAMs models were more effective than GLMs in understanding the effect of oceanographic factors on skipjack tuna distribution and abundance, as shown in Tables 1 and 2. The result of the GAM plots shows the impact of each predictor on schooling density of skipjack tuna as shown in Figures 5. The observed data points are represented by the rug plot on the horizontal axis, while the thin line shows the fitted function, and the grey shading represents the 95% confidence interval (Safruddin 2013).

Table 1. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GAMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<2e-16 ***	6054.183	20.400
SSC	SSC	2.22e-06 ***	6121.052	8.400
Depth	Depth	0.000109 ***	6132.647	4.970
SST + SSC	SST	2.46e-15 ***	6048.045	21.900
	SSC	0.000293 ***		
SST + Depth	SST	2.12e-14 ***	6067.725	17.300
	Depth	0.296		
SSC + Depth	SSC	0.000899 ***	6121.672	8.350
	Depth	0.236307		
SST + SSC + Depth	SST	2.44e-15 ***	6049.831	21.900
	SSC	0.000289 ***		
	Depth	0.832189		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Figure 5 describes the impact of oceanographic conditions on skipjack tuna distribution. Around 29.5–30.5°C, the SST (Figure 5a) had a noticeable positive effect on skipjack tuna distribution. The confidence intervals are broader because there are fewer data points at 30.5–31.0°C. In the SSC plot (Figure 5b), there was a beneficial influence on school distribution in the SSC ranges of 0.25–0.35 mgm^{-3}. A consistent influence on skipjack tuna distribution was seen at a depth of 50–2,000 m (Figure 5c). The study also found that models combining SST and SSC produced the most significant model prediction, with the lowest AIC and highest CDE (Figure 5d). Skipjack tuna distribution in the Northern Pacific Ocean near Japan waters had SST and SSC optimal values of 20.5–26°C and 0.3–0.37 mgm^{-3}, respectively, according to Mugo (2010). The findings of this study corroborated those of Zainuddin et al. (2017), who discovered that the distribution of skipjack tuna in the coastal area was primarily around 50 m depth.

Table 2. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GLMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<2e-16 ***	6083.072	12.960
SSC	SSC	0.89413	6154.549	0.194
Depth	Depth	0.17566	6152.724	0.165
SST + SSC	SST	<2e-16 ***	6084.600	12.870
	SSC	0.494		
SST + Depth	SST	<2e-16 ***	6084.987	12.800
	Depth	0.772		
SSC + Depth	SSC	0.385	6153.966	0.117
	Depth	0.109		
SST + SSC + Depth	SST	<2e-16***	6085.819	12.830
	SSC	0.282		
	Depth	0.379		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

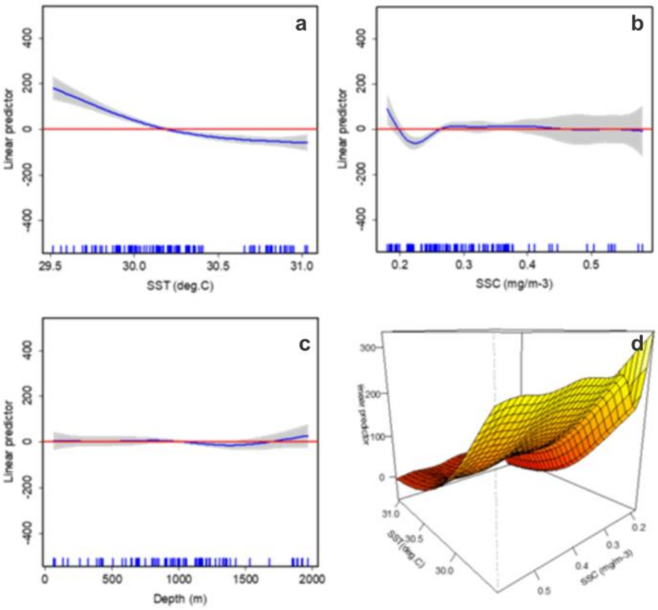

Figure 4. Skipjack tuna distribution responses of oceanographic factors; (a) SST, (b) SSC, (c) depth, and (d) best model predictor.

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Discussion

Oceanographic conditions such as the SST, which have the most significant impact on the growth stages of fish and their distribution (Yuniarti et al. 2013; Syah et al. 2020), play a main role in the natural oscillations of skipjack tuna stocks. As a result, SST is a great indicator for the fishing ground of skipjack tuna to have been used by fishermen and researchers for decades. Furthermore, changes in oceanic (physical and biological) parameters may significantly impact migration patterns and fish growth (Safruddin et al. 2018).

Since the SST in the research region may vary, measurements should be obtained frequently. More samples may be required to accomplish this goal. Therefore, one of the objectives of this research was to determine how oceanographic data can be used in research (e.g., correlation between skipjack tuna distribution and abundance). Temperature fluctuations are often linked to the biological richness (Iskandar et al. 2017; Takarina et al. 2018), such as anchovy distribution and abundance as the prey for skipjack tuna, and they have an important influence on fish physiology (Kunarso et al. 2011; Olson et al. 2016; Duffy et al. 2017).

Satellite remote sensing imagery directly provides horizontal and large-area information on oceanographic conditions, which may be utilized to understand oceanographic processes in the surface water better. The combination of satellite data with acoustic technology will, of course, increase the accuracy of the data. For example, CTD and satellite data are combined when conducting data observations (Safruddin 2013). As a result, four-year datasets of oceanographic conditions (SST, SSC, and water depth) on skipjack tuna position were employed, with scattered plots and optimal ranges indicating a possible association among all variables observed, as shown in Figure 5.

Skipjack tuna can be found in coastal areas, sometimes in great numbers, particularly in upwelling areas (Sari et al. 2018; Wijaya et al. 2020). The study detailed the interaction between skipjack tuna and their oceanographic variables, considering the aspect of temporal and spatial scales to comprehend the numerous processes involved and how they might be utilized to model their dynamics and forecast their abundance (Prista et al. 2011; Selvaraj et al. 2020).

Oceanographic conditions are essential variables to assess the abundance of fish in the waters, especially skipjack tuna, representing the original habitats. The distribution of skipjack tuna observed during the daytime is closely related to the dynamics of oceanographic variables and fishing operations in the Bone Gulf. As shown in Tables 1 and 2 and Figure 5, the effect of oceanographic parameters on the abundance and distribution of skipjack tuna is also a reference for water depths. The p-value, AIC, and CDE can all be used to assess the impact of changing oceanographic conditions on skipjack tuna CPUE. As a result, oceanographic variables connected to skipjack tuna distribution are critical for understanding skipjack tuna habitat preferences.

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Oceanographic phenomena in the waters, such as frontal oceanic zones, eddies, and upwelling areas, often occur with different characteristics as seen in the Bone Gulf and the Flores Sea (Zainuddin et al. 2017, 2019; Hidayat and Zainuddin 2018; Hidayat et al. 2019b). This event makes the waters very dynamic and affects the horizontal distribution of fish in the Bone Gulf. The dynamic oceanographic parameters in this area produce highly productive habitats and serve as foraging grounds for various commercially and ecologically important species such as anchovies and skipjack tuna (Safruddin et al 2018; Hidayat et al 2019b)

The results of this study indicate that the SST tolerance value for skipjack tuna is in the range of 29.5–30.5°C and in the range of 0.25–0.35 mgm^{-3} for SSC parameters (Figures 5a and 5b). However, in addition to SST and SSC, Indonesian Throughflow (ITF) and Asian monsoons also influence the location of the optimum habitat for skipjack tuna (Gordon 2005). Changes in the value of SST in the waters are heavily influenced by the seasonal cycle, in contrast to the SSC, which is not influenced much by the seasonal cycle. Therefore, the migration of skipjack tuna in the northern waters of the Bone Gulf is thought to have followed the mass movement of water in the southeast monsoon, occupying relatively warm areas in offshore waters.

Based on the lowest AIC value and the highest CDE, the GAM nonlinear model is the best statistical model to understand the effect of oceanographic parameters on the distribution and abundance of skipjack tuna. This study is also supported by previous findings in the Makassar Strait, which reported that the GAM model effectively assessed the effect of oceanographic parameters on skipjack tuna (Hidayat et al. 2019a) and small pelagic fish such as anchovies in the Bone Gulf (Safruddin et al. 2018).

Conclusion

This study concludes that the GAM statistical model has succeeded in explaining the effect of oceanographic parameters on the distribution of skipjack tuna in the Bone Gulf. This study also shows the vital role of oceanographic parameters in understanding the habitat of skipjack tuna related to its abundance and distribution in the waters. The distribution of skipjack tuna in the ocean shows a strong relationship with several parameters such as the SST, SSC, and water depth. Suitable or optimal conditions for skipjack tuna represented skipjack fishing areas during the study in the southeast monsoon period. Oceanographic parameters associated with fish catches correspond to the spatial and temporal distribution of skipjack tuna and have become a hot topic of discussion worldwide (Andrade 2003; Mugo et al. 2010; Zainuddin et al. 2019). From the results of this study, it can be suggested that management decisions to increase fishery yields need to consider oceanographic conditions and characteristics in the waters.

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The use of statistical models in identifying skipjack tuna habitat characteristics during the Southeast Monsoon in the Bone Gulf, Indonesia

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Abstract. This study aimed to explore the relationship between the oceanographic factors and the distribution and abundance of skipjack tuna obtained by pole and line fishing in the Bone Gulf, Indonesia. The research was conducted during the southeast monsoon season (April–September) from 2015 until 2018. Three oceanographic parameters were used to understand this relationship, i.e., Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), and water depth. Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) used to predict the spatial pattern of the skipjack tuna showed that all considered parameters significantly influenced the distribution of skipjack tuna in the study area. The fish are mostly distributed from coastal to offshore areas, ranging between 50 to 2,000 meters and even wider. The concentration tends to be high within the range of 29.5 to 30.5°C of SST, 0.25 to 0.35 mgm^{-3} of SSC, and 500 to 1,000 meters of water depth. The research also found that the skipjack tuna migration to the Bone Gulf may have followed the current water interruption during the southeast monsoon, for preferred warmer temperatures and lower primary productivity waters in the offshore areas. This may represent the optimal habitat of the skipjack tuna during this period.

Keywords: oceanographic factors, pole and line, skipjack tuna, statistical models.

Abbreviations: Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), Catch Per Unit Effort (CPUE), Generalized Additive Models (GAMs), Generalized Linear Models (GLMs), Akaike Information Criterion (AIC), Cumulative Deviance Explained (CDE)

Running title: Statistical Model for Skipjack Habitat

INTRODUCTION

Skipjack tuna (*Katsuwonus pelamis*) is the most crucial target catch of marine fisheries in the world's oceans (Galland et al. 2016). Large schools of adult skipjack tuna are often associated with juvenile yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (IOTC 2020). Skipjack tuna is a highly migratory pelagic species inhabiting all tropical and subtropical waters (Artetxe-Arrate et al. 2020). However, they are found mainly in the tropical areas of the Atlantic, Indian, and Pacific Oceans, with the most incredible abundance seen near the equator. Since juvenile yellowfin and bigeye tuna often school with adult skipjack tuna, they are caught by purse seine and pole and line vessels whose main target is skipjack tuna (Hidayat et al. 2019; IOTC 2019; Safruddin et al. 2020).

The dynamics of oceanographic factors could affect the natural fluctuations in the distribution and abundance of skipjack tuna in the coastal and offshore areas (Mugo et al. 2010; Tseng et al. 2010; Wang et al. 2016). The distribution could also be influenced by the abundance of small pelagic fish such as anchovy in the same area (Safruddin et al. 2018). Therefore, there is an urgent need for information on the effects of oceanographic factors on skipjack tuna distribution (Andrade and Garcia 1999) to predict fishing ground potential zones for sustainable skipjack tuna fishery in the study area.

Statistical models such as generalized additive models (GAMs) and generalized linear models (GLMs) can be the most useful methods for determining the fish distribution in relation to oceanographic factors such as the sea surface temperature (SST), sea surface chlorophyll-a (SSC), and water depth (Safruddin 2013; Safruddin et al. 2018; Selao et al. 2019).

The Bone Gulf is one of the best skipjack tuna habitats in Indonesian waters, with the peak fishing season lasting from early April until the end of September (southeast monsoon). Although skipjack tuna is an iconic species in the Bone Gulf, its local availability is a key factor for the pole and line fishery economy. However, there is a lack of information about its distribution, both spatially and temporally. Hence, this study is an attempt to investigate the availability of skipjack tuna caught using pole and line fishing gear under various oceanographic conditions and to discuss the oceanographic elements impacting skipjack tuna distribution by applying statistical models.

MATERIALS AND METHODS

Study area

The study area was located in the Bone Gulf (3–5°S) and (120–122°E), South Sulawesi, Indonesia (Figure 1). The field surveys used the pole and line method (local commercial fisheries) to investigate the fishing ground positions and the number of skipjack tuna catches during the study. Oceanography observations (satellite imagery data) were conducted monthly during the southeast monsoon (April–September) from 2015 until 2018.

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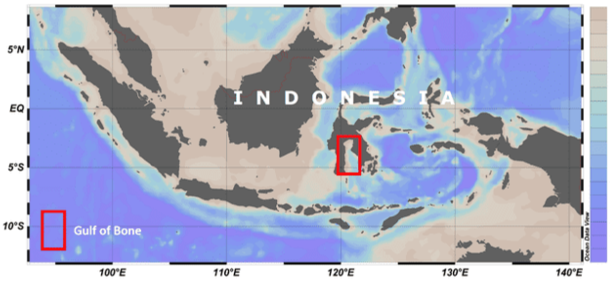

Figure 1. Map of the Indonesian seas with the red box representing the study area.

Procedures

Data Collection

In-situ data were obtained through a scientific survey at the fishing base at Murante fish landing site, Luwu district. We gathered the fishery data from 508 fishing ground positions. A global positioning system (GPS) was used to determine fishing ground coordinates (latitude and longitude). The in-situ field data consisted of the fishing position and catch per unit efforts (CPUEs). The oceanographic parameters (SST, and SSC) were obtained from satellite oceanography imagery data of high-resolution Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS), with a spatial resolution of 4 km, from 2015 until 2018 (April–September). The water depth data was gained from the ETOPO1 satellite database. In this study, we used monthly temporal resolution. Furthermore, the SST and SSC averaged during southeast monsoon were mapped as shown in Figures 2 and 3, respectively.

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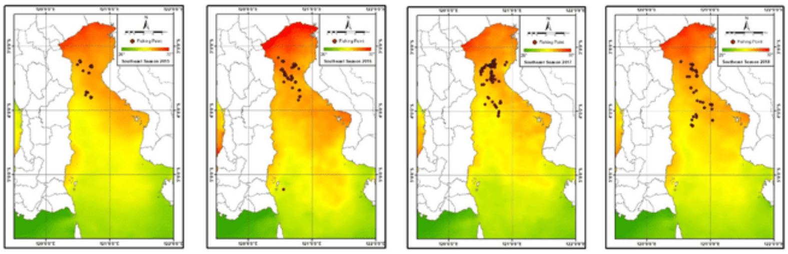

Figure 2. The profiles of SST average during southeast monsoon from 2015 until 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters.

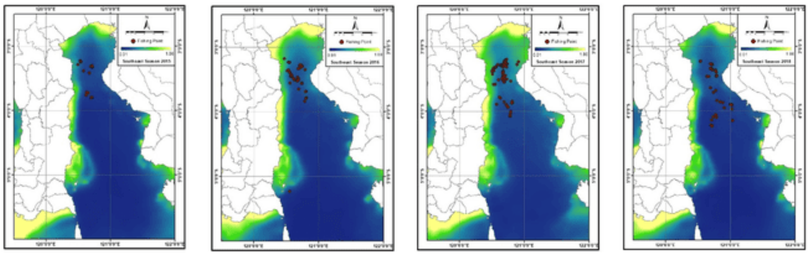

Figure 3. The profiles of SSC average during southeast monsoon from 2015 to 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters.

Data Analysis

To determine the effect of oceanographic parameters on horizontal distributions of skipjack tuna in the sea, statistical models (Hastie and Tibshirani 1990) were used for the CPUE and oceanographic datasets. The models, such as GAMs and GLMs, were created using the MGCV package in R-studio (Wood 2006) to predict the spatial patterns of skipjack tuna. The response variable used skipjack tuna catches (CPUE/fishing trip), and the predictor used oceanographic parameters (SST, SSC, and depth).

The hypothesized interactions between oceanographic parameters and skipjack tuna distribution are most likely non-linear. GAM was employed as an experimental technique to determine the forms of the associations. The connections between the skipjack distribution and each predictor (SST, SSC, and depth) were also determined. In a GLM, proper functions were utilized to identify these forms in the linear model, as indicated in Equations (1) and (2) (Safruddin 2013).

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (SSC) + s3\ (depth) + \varepsilon \quad \text{(GAM model)} \qquad (1)$$

$$g(\mu i) = \beta 0 + \beta 1\ (SST) + \beta 2\ (SSC) + \beta 3\ (depth) + \varepsilon \quad \text{(GLM model)} \qquad (2)$$

where g is the link function, μi is the expected value of the dependent variable for the presence of skipjack tuna (CPUE), α0 and β0 are the respective model's constant, sn is the predictor variable's smoothing function, ε is a random error term, and βn is the vector of model coefficients.

The Gaussian family with identical link functions was chosen since the skipjack tuna CPUE has a continuous distribution. Models were created from the ground up, with only one independent component such as SST, and predictor components were added later. Model selection was influenced by the predictor's significance, Akaike Information Criterion (AIC) reduction, and the deviance explained value. The best model was chosen from a group of seven to build the GAMs/GLMs. The GAMs/GLMs model was utilized to compare the results of the prediction models using a statistical criterion. They were also used to explain all observations with multiple variables, including inter-variable correlations (Safruddin 2013).

RESULTS AND DISCUSSION

Skipjack tuna fishing ground

Skipjack tuna fishing grounds were mapped on latitude and longitude scales, with SST, SSC, and depth overlay (Figures 2–4). CPUE marks the position along the overlay in Figures 2–4, and each school is designated as a single point. Map contours with high SST, SSC, and depth, or the opposite, were also discovered.

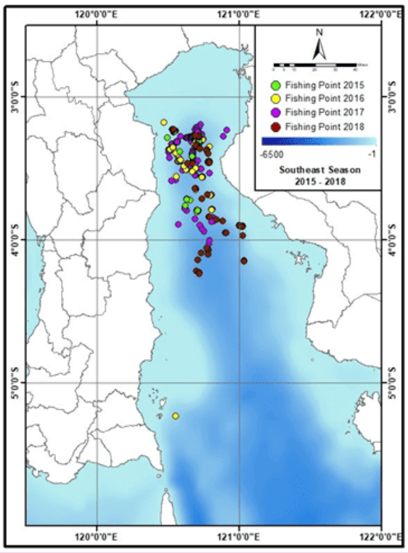

Figure 4. The profiles of bathymetric overlay with the skipjack tuna distribution during southeast monsoon from 2015 to 2018 in the Bone Gulf waters.

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The lowest SST and the highest SSC occur every year during the southeast monsoon period. The reverse happens in the northwest monsoon season, skipjack tuna was least abundant in the lower SST area (Figure 2) due to changes in water temperature caused by water currents from the Flores Sea entrance to the Bone Gulf. This could be a strategy in biological processes related to fish growth under changing oceanographic conditions. Skipjack tuna stock is positively correlated with oceanographic factors. It is distributed mainly in nearshore areas in the water depth range of 50 to 2,000 m (Figure 4). The horizontal profiles of the SST and SSC structures for the 2015–2018 southeast monsoon season (Figures 2 and 3) are warmer near the coast than offshore. Skipjack schools occupy offshore areas where they prefer relatively higher SST and lower SSC (Figures 2 and 3).

The environmental conditions of skipjack tuna fishing grounds were used for four monthly datasets (April–August). As a result, the preference range suggested a possible association between all examined factors. For example, Figure 4 shows that skipjack tuna were found in temperatures ranging from 29.5 to 31.05°C. Likewise, the skipjack tuna schools concentrated in the narrow ranges of 0.15–1.00 mgm^{-3} with respect to SSC.

Effects of oceanographic factors on skipjack tuna distribution

The oceanographic conditions of the skipjack tuna schooling coordinates were employed in the current study for displaying the area and further analysis. Tables 1 and 2 show the models built using GAMs/GLMs on the skipjack tuna distribution scenarios utilizing predictor parameters (SST, SSC, and depth).

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Tables 1 and 2 present the results for each of the seven GAM and GLM models. Each model's predictor component(s) significantly affected the skipjack tuna distribution in $p < 0.05$ reference levels, except depth as predictor two and three (Table 1). However, only SST substantially contributed to a single model predictor, two model predictors, and three model predictors in GLMs (Table 2). For the final model combination of SST, SSC, and depth, the cumulative deviance explained (CDE) was 21.9% (GAMs) and 12.830% (GLMs), respectively. Thus, Tables 1 and 2 suggest that the influence of oceanographic conditions may explain the fluctuation of skipjack tuna abundance distribution. Additionally, GAMs with higher CDE were well-suited to characterize the influence of oceanographic conditions on skipjack tuna distribution and abundance.

Tables 1 and 2 show the results of GAMs and GLMs, respectively. For both statistical models, the SST had the largest deviance explained among the single variable models. According to AIC (6048.045) and CDE (21.9%), and as the best model predictor of GAM, the combination of SST and SSC predicted relatively more significant variability in skipjack tuna catches. The AIC values for the three-parameter models were low (6049.831) and the most significant deviation explained was 21.9%. SST was the sole predictor model with the lowest AIC (6083.072) and the maximum CDE on the GLMs model (12.870%) and was also found as a combined two-parameter model between SST and SSC. The three-parameter models had the lowest AIC and the highest CDE overall (12.830%). All results produced by combining predictor factors at various levels revealed an increase or decrease in CDE and a higher AIC value of variation.

GAMs models were more effective than GLMs in understanding the effect of oceanographic factors on skipjack tuna distribution and abundance, as shown in Tables 1 and 2. The result of the GAM plots shows the impact of each predictor on schooling density of skipjack tuna as shown in Figures 5. The observed data points are represented by the rug plot on the horizontal axis, while the thin line shows the fitted function, and the grey shading represents the 95% confidence interval (Safruddin 2013).

Table 1. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GAMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<2e-16 ***	6054.183	20.400
SSC	SSC	2.22e-06 ***	6121.052	8.400
Depth	Depth	0.000109 ***	6132.647	4.970
SST + SSC	SST	2.46e-15 ***	6048.045	21.900
	SSC	0.000293 ***		
SST + Depth	SST	2.12e-14 ***	6067.725	17.300
	Depth	0.296		
SSC + Depth	SSC	0.000899 ***	6121.672	8.350
	Depth	0.236307		
SST + SSC + Depth	SST	2.44e-15 ***	6049.831	21.900
	SSC	0.000289 ***		
	Depth	0.832189		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Figure 5 describes the impact of oceanographic conditions on skipjack tuna distribution. Around 29.5–30.5°C, the SST (Figure 5a) had a noticeable positive effect on skipjack tuna distribution. The confidence intervals are broader because there are fewer data points at 30.5–31.0°C. In the SSC plot (Figure 5b), there was a beneficial influence on school distribution in the SSC ranges of 0.25–0.35 mgm^{-3}. A consistent influence on skipjack tuna distribution was seen at a depth of 50–2,000 m (Figure 5c). The study also found that models combining SST and SSC produced the domost significant model prediction, with the lowest AIC and highest CDE (Figure 5d). Skipjack tuna distribution in the Northern Pacific Ocean near Japan waters had SST and SSC optimal values of 20.5–26°C and 0.3–0.37 mgm^{-3}, respectively, according to Mugo (2010). The findings of this study corroborated those of Zainuddin et al. (2017), who discovered that the distribution of skipjack tuna in the coastal area was primarily around 50 m depth.

Table 2. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GLMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<2e-16 ***	6083.072	12.960
SSC	SSC	0.89413	6154.549	0.194
Depth	Depth	0.17566	6152.724	0.165
SST + SSC	SST	<2e-16 ***	6084.600	12.870
	SSC	0.494		
SST + Depth	SST	<2e-16 ***	6084.987	12.800
	Depth	0.772		
SSC + Depth	SSC	0.385	6153.966	0.117
	Depth	0.109		
SST + SSC + Depth	SST	<2e-16***	6085.819	12.830
	SSC	0.282		
	Depth	0.379		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

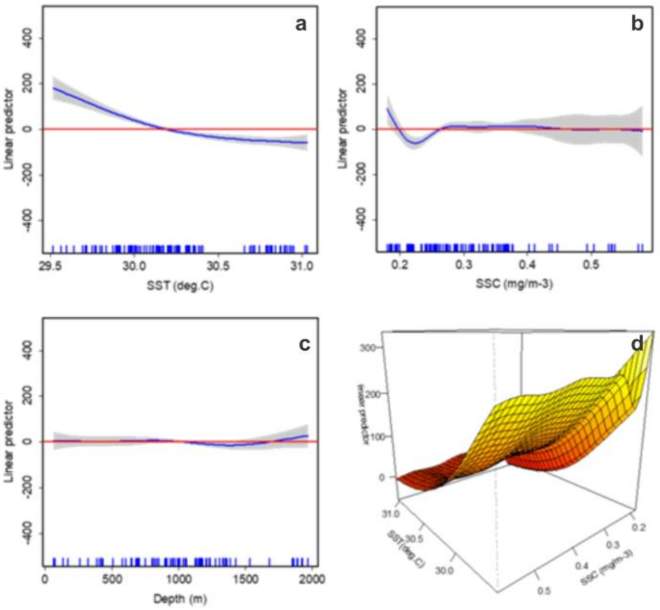

Figure 4. Skipjack tuna distribution responses of oceanographic factors; (a) SST, (b) SSC, (c) depth, and (d) best model predictor.

Discussion

Oceanographic conditions such as the SST, which have the most significant impact on the growth stages of fish and their distribution (Yuniarti et al. 2013; Syah et al. 2020), play a main role in the natural oscillations of skipjack tuna stocks. As a result, SST is a great indicator for the fishing ground of skipjack tuna to have been used by fishermen and researchers for decades. Furthermore, changes in oceanic (physical and biological) parameters may significantly impact migration patterns and fish growth (Safruddin et al. 2018).

Since the SST in the research region may vary, measurements should be obtained frequently. More samples may be required to accomplish this goal. Therefore, one of the objectives of this research was to determine how oceanographic data can be used in research (e.g., correlation between skipjack tuna distribution and abundance). Temperature fluctuations are often linked to the biological richness (Iskandar et al. 2017; Takarina et al. 2018), such as anchovy distribution and abundance as the prey for skipjack tuna, and they have an important influence on fish physiology (Kunarso et al. 2011; Olson et al. 2016; Duffy et al. 2017).

Satellite remote sensing imagery directly provides horizontal and large-area information on oceanographic conditions, which may be utilized to understand oceanographic processes in the surface water better. The combination of satellite data with acoustic technology will, of course, increase the accuracy of the data. For example, CTD and satellite data are combined when conducting data observations (Safruddin 2013). As a result, four-year datasets of oceanographic conditions (SST, SSC, and water depth) on skipjack tuna position were employed, with scattered plots and optimal ranges indicating a possible association among all variables observed, as shown in Figure 5.

Skipjack tuna can be found in coastal areas, sometimes in great numbers, particularly in upwelling areas (Sari et al. 2018; Wijaya et al. 2020). The study detailed the interaction between skipjack tuna and their oceanographic variables, considering the aspect of temporal and spatial scales to comprehend the numerous processes involved and how they might be utilized to model their dynamics and forecast their abundance (Prista et al. 2011; Selvaraj et al. 2020).

Oceanographic conditions are essential variables to assess the abundance of fish in the waters, especially skipjack tuna, representing the original habitats. The distribution of skipjack tuna observed during the daytime is closely related to the dynamics of oceanographic variables and fishing operations in the Bone Gulf. As shown in Tables 1 and 2 and Figure 5, the effect of oceanographic parameters on the abundance and distribution of skipjack tuna is also a reference for water depths. The p-value, AIC, and CDE can all be used to assess the impact of changing oceanographic conditions on skipjack tuna CPUE. As a result, oceanographic variables connected to skipjack tuna distribution are critical for understanding skipjack tuna habitat preferences.

Oceanographic phenomena in the waters, such as frontal oceanic zones, eddies, and upwelling areas, often occur with different characteristics as seen in the Bone Gulf and the Flores Sea (Zainuddin et al. 2017, 2019; Hidayat and Zainuddin 2018; Hidayat et al. 2019b). This event makes the waters very dynamic and affects the horizontal distribution of fish in the Bone Gulf. The dynamic oceanographic parameters in this area produce highly productive habitats and serve as foraging grounds for various commercially and ecologically important species such as anchovies and skipjack tuna (Safruddin et al 2018; Hidayat et al 2019b)

The results of this study indicate that the SST tolerance value for skipjack tuna is in the range of 29.5–30.5°C and in the range of 0.25–0.35 mgm^{-3} for SSC parameters (Figures 5a and 5b). However, in addition to SST and SSC, Indonesian Throughflow (ITF) and Asian monsoons also influence the location of the optimum habitat for skipjack tuna (Gordon 2005). Changes in the value of SST in the waters are heavily influenced by the seasonal cycle, in contrast to the SSC, which is not influenced much by the seasonal cycle. Therefore, the migration of skipjack tuna in the northern waters of the Bone Gulf is thought to have followed the mass movement of water in the southeast monsoon, occupying relatively warm areas in offshore waters.

Based on the lowest AIC value and the highest CDE, the GAM nonlinear model is the best statistical model to understand the effect of oceanographic parameters on the distribution and abundance of skipjack tuna. This study is also supported by previous findings in the Makassar Strait, which reported that the GAM model effectively assessed the effect of oceanographic parameters on skipjack tuna (Hidayat et al. 2019a) and small pelagic fish such as anchovies in the Bone Gulf (Safruddin et al. 2018).

Conclusion

This study concludes that the GAM statistical model has succeeded in explaining the effect of oceanographic parameters on the distribution of skipjack tuna in the Bone Gulf. This study also shows the vital role of oceanographic parameters in understanding the habitat of skipjack tuna related to its abundance and distribution in the waters. The distribution of skipjack tuna in the ocean shows a strong relationship with several parameters such as the SST, SSC, and water depth. Suitable or optimal conditions for skipjack tuna represented skipjack fishing areas during the study in the southeast monsoon period. Oceanographic parameters associated with fish catches correspond to the spatial and temporal distribution of skipjack tuna and have become a hot topic of discussion worldwide (Andrade 2003; Mugo et al. 2010; Zainuddin et al. 2019). From the results of this study, it can be suggested that management decisions to increase fishery yields need to consider oceanographic conditions and characteristics in the waters.

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The use of statistical models in identifying skipjack tuna habitat characteristics during the Southeast Monsoon in the Bone Gulf, Indonesia

Abstract. Skipjack tuna (*Katsuwonus pelamis*) is the main fishery product in the Bone Gulf, Indonesia, since it has high economic value and is widely accepted by the market. The migration of skipjack tuna can be described by oceanographic dynamics, influenced by seasonal changes. This study aimed to explore the relationship between the oceanographic factors and the distribution and abundance of skipjack tuna obtained by pole and line fishing in the Bone Gulf, Indonesia. The research was conducted during the southeast monsoon season (April–September) from 2015 until 2018. Three oceanographic parameters were used to understand this relationship, i.e., Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), and water depth. Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) used to predict the spatial pattern of the skipjack tuna showed that all considered parameters significantly influenced the distribution of skipjack tuna in the study area. The fish are mostly distributed from coastal to offshore areas, ranging between 50 to 2,000 meters and even wider. The concentration tends to be high within the range of 29.5 to 30.5°C of SST, 0.25 to 0.35 mgm^{-3} of SSC, and 500 to 1,500 meters of water depth. The research also found that the skipjack tuna migration to the Bone Gulf may have followed the current water interruption during the southeast monsoon, for preferred warmer temperatures and lower primary productivity waters in the offshore areas. This factor may represent the optimal habitat of skipjack tuna during the period and can be the basis for determining the skipjack fishing schedule in the Bone Gulf.

Keywords: Fishing schedule, Oceanographic factors, Satellite Data, Skipjack Tuna (*Katsuwonus pelamis*) Habitat, Southeast monsoon season.

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Abbreviations: Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), Catch Per Unit Effort (CPUE), Generalized Additive Models (GAMs), Generalized Linear Models (GLMs), Akaike Information Criterion (AIC), Cumulative Deviance Explained (CDE)

Running title: Statistical Model for Skipjack Habitat

INTRODUCTION

Skipjack tuna (*Katsuwonus pelamis*) is the most crucial target catch of marine fisheries in the world's oceans (Galland et al. 2016). Large schools of adult skipjack tuna are often associated with juvenile yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (IOTC 2020). Skipjack tuna is a highly migratory pelagic species inhabiting all tropical and subtropical waters (Artetxe-Arrate et al. 2020). However, they are found mainly in the tropical areas of the Atlantic, Indian, and Pacific Oceans, with the most incredible abundance seen near the equator. Since juvenile yellowfin and bigeye tuna often school with adult skipjack tuna, they are caught by purse seine and pole and line vessels whose main target is skipjack tuna (Hidayat et al. 2019; IOTC 2019; Safruddin et al. 2020).

The dynamics of oceanographic factors could affect the natural fluctuations in the distribution and abundance of skipjack tuna in the coastal and offshore areas (Mugo et al. 2010; Tseng et al. 2010; Wang et al. 2016). The distribution could also be influenced by the abundance of small pelagic fish such as anchovy in the same area (Safruddin et al. 2018). Therefore, there is an urgent need for information on the effects of oceanographic factors on skipjack tuna distribution (Andrade and Garcia 1999) to predict fishing ground potential zones for sustainable skipjack tuna fishery in the study area.

Statistical models such as generalized additive models (GAMs) and generalized linear models (GLMs) can be the most useful methods for determining the fish distribution in relation to oceanographic factors such as the sea surface temperature (SST), sea surface chlorophyll-a (SSC), and water depth (Safruddin 2013; Safruddin et al. 2018; Selao et al. 2019).

The Bone Gulf is one of the best skipjack tuna habitats in Indonesian waters (Zainuddin et al. 2020), with the peak fishing season lasting from early April until the end of September (southeast monsoon). Although skipjack tuna is an iconic species in the Bone Gulf, its local availability is a key factor for the pole and line fishery economy. However, there is a lack of information about its distribution, both spatially and temporally. Hence, this study is an attempt to investigate

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MATERIALS AND METHODS

Study area

The study area was located in the Bone Gulf (3–5°S) and (120–122°E), South Sulawesi, Indonesia (Figure 1). The field surveys used the pole and line method (local commercial fisheries) to investigate the fishing ground positions and the number of skipjack tuna catches during the study. Oceanography and bathymetric observations (satellite imagery data) were conducted monthly during the southeast monsoon (April–September) from 2015 until 2018. This study only focuses on fishing activities in the southeast monsoon, which is due to the peak season for skipjack fishing in the Bone Gulf takes place in the southeast monsoon.

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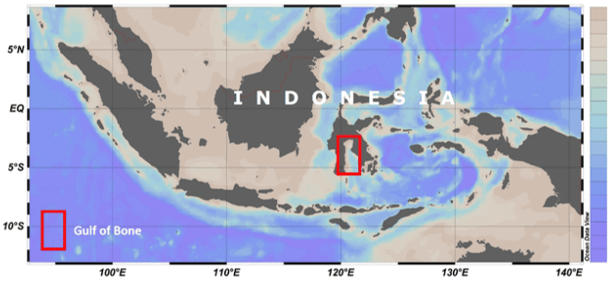

Figure 1. Map of the Indonesian seas with the red box representing the study area.

Procedures

Data Collection

In-situ data were obtained through a scientific survey at the fishing base at Murante fish landing site, Luwu district. We gathered the fishery data from 508 fishing ground positions. A global positioning system (GPS) was used to determine fishing ground coordinates (latitude and longitude). The in-situ field data consisted of the fishing position and catch per unit efforts (CPUEs). The oceanographic parameters (SST, and SSC) were obtained from satellite oceanography imagery data of high-resolution Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS), with a spatial resolution of 4 km, from 2015 until 2018 (April–September). The water depth data was gained from the ETOPO1 (Amante and Eakins 2009) satellite database. In this study, we used monthly temporal resolution. Furthermore, the SST and SSC averaged during southeast monsoon were mapped as shown in Figures 2 and 3, respectively.

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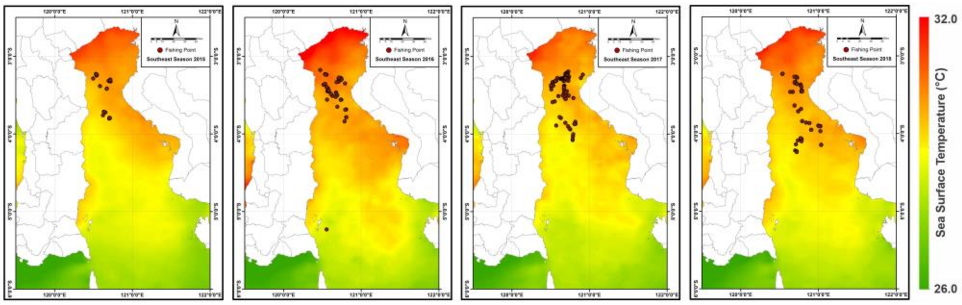

Figure 2. The profiles of SST average during southeast monsoon from 2015 until 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters. The gradient from green (low temperature) to red (high temperature) illustrates variations in SST in the waters. The red dot on the maps represents the location of the skipjack tuna fishing coordinates during the study

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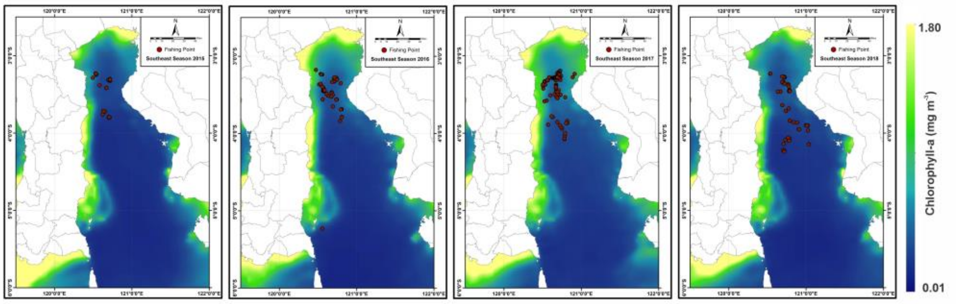

Figure 3. The profiles of SSC average during southeast monsoon from 2015 to 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters. The gradient from blue (low concentration) to yellow (high concentration) illustrates variations in SSC in the waters. The red dot on the maps represents the location of the skipjack tuna fishing coordinates during the study

Data Analysis

To determine the effect of oceanographic parameters on horizontal distributions of skipjack tuna in the sea, statistical models (Hastie and Tibshirani 1990) were used for the CPUE and oceanographic datasets. The models, such as GAMs and GLMs, were created using the MGCV package in R-studio (Wood 2006) to predict the spatial patterns of skipjack tuna. The response variable used skipjack tuna catches (CPUE/fishing trip), and the predictor used oceanographic parameters (SST, SSC, and depth).

The hypothesized interactions between oceanographic parameters and skipjack tuna distribution are most likely non-linear. GAM was employed as an experimental technique to determine the forms of the associations. The connections between the skipjack distribution and each predictor (SST, SSC, and depth) were also determined. In a GLM, proper functions were utilized to identify these forms in the linear model, as indicated in Equations (1) and (2) (Safruddin 2013).

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (SSC) + s3\ (depth) + \varepsilon \quad \text{(GAM model)} \qquad (1)$$

$$g(\mu i) = \beta 0 + \beta 1\ (SST) + \beta 2\ (SSC) + \beta 3\ (depth) + \varepsilon \quad \text{(GLM model)} \qquad (2)$$

where g is the link function, μi is the expected value of the dependent variable for the presence of skipjack tuna (CPUE), α0 and β0 are the respective model’s constant, sn is the predictor variable’s smoothing function, ε is a random error term, and βn is the vector of model coefficients.

The Gaussian family with identical link functions was chosen since the skipjack tuna CPUE has a continuous distribution. Models were created from the ground up, with only one independent component such as SST, and predictor components were added later. Model selection was influenced by the predictor's significance, Akaike Information Criterion (AIC) reduction, and the deviance explained value. The best model was chosen from a group of seven to build the GAMs/GLMs. The GAMs/GLMs model was utilized to compare the results of the prediction models using a statistical criterion. They were also used to explain all observations with multiple variables, including inter-variable correlations (Safruddin 2013).

RESULTS AND DISCUSSION

Skipjack tuna fishing ground

Skipjack tuna fishing grounds were mapped on latitude and longitude scales, with SST, SSC, and depth overlay (Figures 2–4). CPUE marks the position along the overlay in Figures 2–4, and each school is designated as a single point. Map contours with high SST, SSC, and depth, or the opposite, were also discovered.

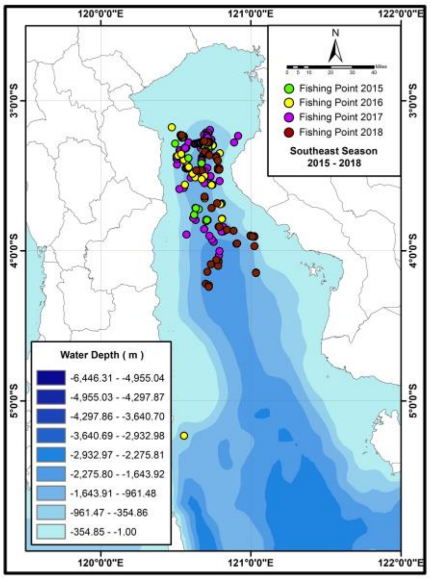

Figure 4. The profiles of bathymetric overlay with the skipjack tuna distribution during southeast monsoon from 2015 to 2018 in the Bone Gulf waters.

The lowest SST and the highest SSC occur every year during the southeast monsoon period. The reverse happens in the northwest monsoon season, skipjack tuna was least abundant in the lower SST area (Figure 2) due to changes in water temperature caused by water currents from the Flores Sea entrance to the Bone Gulf. This could be a strategy in biological processes related to fish growth under changing oceanographic conditions. Skipjack tuna stock is positively correlated with oceanographic factors. It is distributed mainly in nearshore areas in the water depth range of 50 to 2,000 m (Figure 4). The horizontal profiles of the SST and SSC structures for the 2015–2018 southeast monsoon season (Figures 2 and 3) are warmer near the coast than offshore. Skipjack schools occupy offshore areas where they prefer relatively higher SST and lower SSC (Figures 2 and 3).

The environmental conditions of skipjack tuna fishing grounds were used for four monthly datasets (April–August). As a result, the preference range suggested a possible association between all examined factors. For example, Figure 2 shows that skipjack tuna were found in temperatures ranging from 29.5 to 31.05°C. Likewise, the skipjack tuna schools concentrated in the narrow ranges of 0.15–1.00 mg.m^{-3} with respect to SSC (Figure 3). As for the depth of water, skipjack is found in waters with a depth of 50 – 2,000 meters (Figure 4).

Effects of oceanographic factors on skipjack tuna distribution

The oceanographic conditions of the skipjack tuna schooling coordinates were employed in the current study for displaying the area and further analysis. Tables 1 and 2 show the models built using GAMs/GLMs on the skipjack tuna distribution scenarios utilizing predictor parameters (SST, SSC, and depth). Tables 1 and 2 present the results for each of the seven GAM and GLM models. Each model's predictor component(s) significantly affected the skipjack tuna distribution in $p<0.05$ reference levels, except depth as predictor two and three (Table 1). However, only SST substantially contributed to a single model predictor, two model predictors, and three model predictors in GLMs (Table 2). For the final model combination of SST, SSC, and depth, the cumulative deviance explained (CDE) was 21.9% (GAMs) and 12.830% (GLMs), respectively. Thus, Tables 1 and 2 suggest that the influence of oceanographic conditions may explain the fluctuation of skipjack tuna abundance distribution. Additionally, GAMs with higher CDE were well-suited to characterize the influence of oceanographic conditions on skipjack tuna distribution and abundance.

Tables 1 and 2 show the results of GAMs and GLMs, respectively. For both statistical models, the SST had the largest deviance explained among the single variable models. According to AIC (6048.045) and CDE (21.9%), and as the best model predictor of GAM, the combination of SST and SSC predicted relatively more significant variability in skipjack tuna catches. The AIC values for the three-parameter models were low (6049.831) and the most significant deviation explained was 21.9%. SST was the sole predictor model with the lowest AIC (6083.072) and the maximum CDE on the GLMs model (12.870%) and was also found as a combined two-parameter model between SST and SSC. The three-parameter models had the lowest AIC and the highest CDE overall (12.830%). All results produced by combining predictor factors at various levels revealed an increase or decrease in CDE and a higher AIC value of variation.

GAMs models were more effective than GLMs in understanding the effect of oceanographic factors on skipjack tuna distribution and abundance, as shown in Tables 1 and 2. The result of the GAM plots shows the impact of each predictor on schooling density of skipjack tuna as shown in Figures 5. The observed data points are represented by the rug plot on the horizontal axis, while the thin line shows the fitted function, and the grey shading represents the 95% confidence interval (Safruddin 2013).

Table 1. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GAMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<0.001 ***	6054.183	20.400
SSC	SSC	<0.001 ***	6121.052	8.400
Depth	Depth	<0.001 ***	6132.647	4.970
SST + SSC	SST	<0.001 ***	6048.045	21.900
	SSC	<0.001 ***		
SST + Depth	SST	<0.001 ***	6067.725	17.300
	Depth	0.296		
SSC + Depth	SSC	<0.001 ***	6121.672	8.350
	Depth	0.236		
SST + SSC + Depth	SST	<0.001 ***	6049.831	21.900
	SSC	<0.001 ***		
	Depth	0.832		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

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Figure 5 describes the impact of oceanographic conditions on skipjack tuna distribution. Around 29.5–30.5°C, the SST (Figure 5a) had a noticeable positive effect on skipjack tuna distribution. The confidence intervals are broader because there are fewer data points at 30.5–31.0°C. In the SSC plot (Figure 5b), there was a beneficial influence on school distribution in the SSC ranges of 0.25–0.35 mgm^{-3}. A consistent influence on skipjack tuna distribution was seen at a depth of 500–1,500 m (Figure 5c). The study also found that models combining SST and SSC produced the most significant model prediction, with the lowest AIC and highest CDE (Figure 5d). Skipjack tuna distribution in the Northern Pacific Ocean near Japan waters had SST and SSC optimal values of 20.5–26°C and 0.3–0.37 mgm^{-3}, respectively, according to Mugo (2010). The findings of this study corroborated those of Zainuddin et al. (2017), who discovered that the distribution of skipjack tuna in the coastal area was primarily around 50 m depth.

Table 2. Oceanographic factor influences on the skipjack tuna distribution (n=508), according to the GLMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<0.001 ***	6083.072	12.960
SSC	SSC	0.894	6154.549	0.194
Depth	Depth	0.176	6152.724	0.165
SST + SSC	SST	<0.001 ***	6084.600	12.870
	SSC	0.494		
SST + Depth	SST	<0.001 ***	6084.987	12.800
	Depth	0.772		
SSC + Depth	SSC	0.385	6153.966	0.117
	Depth	0.109		
SST + SSC + Depth	SST	<0.001 ***	6085.819	12.830
	SSC	0.282		
	Depth	0.379		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

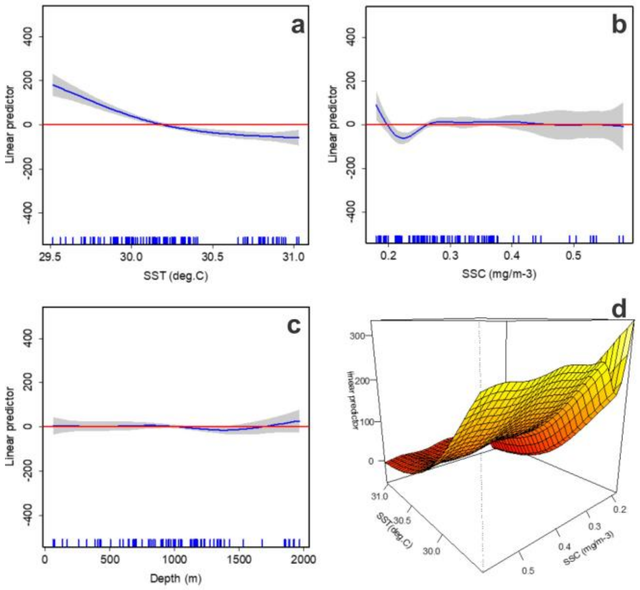

Figure 5. Skipjack tuna distribution responses of oceanographic factors; (a) SST, (b) SSC, (c) depth, and (d) best model predictor. The shaded area is the standard error indicating the 95% confidence interval. The stack of blue vertical lines on the x-axis indicates the density or distribution of the test parameter data. The y-axis is the partial effect of the variable, while the 3D graph depicts a combination model between significant SST and SSC to be the best predictive model.

Discussion

Oceanographic conditions such as the SST, which have the most significant impact on the growth stages of fish and their distribution (Yuniarti et al. 2013; Syah et al. 2020), play a main role in the natural oscillations of skipjack tuna stocks. As a result, SST is a great indicator for the fishing ground of skipjack tuna to have been used by fishermen and researchers for decades. Furthermore, changes in oceanic (physical and biological) parameters may significantly impact migration patterns and fish growth (Safruddin et al. 2018).

Since the SST in the research region may vary, measurements should be obtained frequently. More samples may be required to accomplish this goal. Therefore, one of the objectives of this research was to determine how oceanographic data can be used in research (e.g., correlation between skipjack tuna distribution and abundance). Temperature fluctuations are often linked to the biological richness (Iskandar et al. 2017; Takarina et al. 2018), such as anchovy distribution and abundance as the prey for skipjack tuna, and they have an important influence on fish physiology (Kunarso et al. 2011; Olson et al. 2016; Duffy et al. 2017).

Satellite remote sensing imagery directly provides horizontal and large-area information on oceanographic conditions, which may be utilized to understand oceanographic processes in the surface water better. The combination of satellite data with acoustic technology will, of course, increase the accuracy of the data. For example, CTD and satellite data are combined when conducting data observations (Safruddin 2013). As a result, four-year datasets of oceanographic conditions (SST, SSC, and water depth) on skipjack tuna position were employed, with scattered plots and optimal ranges indicating a possible association among all variables observed, as shown in Figure 5.

Skipjack tuna can be found in coastal areas, sometimes in large numbers, especially in upwelling areas (Sari et al. 2018; Wijaya et al. 2020). This study details the interactions between skipjack tuna and its oceanographic variables taking into account temporal and spatial scale aspects to understand the various processes involved and how they can be used to model dynamics and estimate their abundance (Prista et al. 2011; Selvaraj et al. 2020). The catch data used is the distribution of catches in Bone Bay. Although spatially, several fishing points are located in almost the same area, the dynamics of different oceanographic parameters each year make the description of the range of SST and SSC at each skipjack fishing point experience different.

Oceanographic conditions are essential variables to assess the abundance of fish in the waters, especially skipjack tuna, representing the original habitats. The distribution of skipjack tuna observed during the daytime is closely related to the dynamics of oceanographic variables and fishing operations in the Bone Gulf. As shown in Tables 1 and 2 and Figure 5, the effect of oceanographic parameters on the abundance and distribution of skipjack tuna is also a reference for water depths. The p-value, AIC, and CDE can all be used to assess the impact of changing oceanographic conditions on skipjack tuna CPUE. As a result, oceanographic variables connected to skipjack tuna distribution are critical for understanding skipjack tuna habitat preferences.

Oceanographic phenomena in the waters, such as frontal oceanic zones, eddies, and upwelling areas, often occur with different characteristics as seen in the Bone Gulf and the Flores Sea (Zainuddin et al. 2017, 2019; Hidayat and Zainuddin 2018; Hidayat et al. 2019b). This event makes the waters very dynamic and affects the horizontal distribution of fish in the Bone Gulf. The dynamic oceanographic parameters in this area produce highly productive habitats and serve as foraging grounds for various commercially and ecologically important species such as anchovies and skipjack tuna (Safruddin et al 2018; Hidayat et al 2019b)

The results of this study indicate that the SST tolerance value for skipjack tuna is in the range of 29.5–30.5°C and in the range of 0.25–0.35 mgm^{-3} for SSC parameters (Figures 5a and 5b). However, in addition to SST and SSC, Indonesian Throughflow (ITF) and Asian monsoons also influence the location of the optimum habitat for skipjack tuna (Gordon 2005). Changes in the value of SST in the waters are heavily influenced by the seasonal cycle, in contrast to the SSC, which is not influenced much by the seasonal cycle. Therefore, the migration of skipjack tuna in the northern waters of the Bone Gulf is thought to have followed the mass movement of water in the southeast monsoon, occupying relatively warm areas in offshore waters.

Based on the lowest AIC value and the highest CDE, the GAM nonlinear model is the best statistical model to understand the effect of oceanographic parameters on the distribution and abundance of skipjack tuna. This study is also supported by previous findings in the Makassar Strait, which reported that the GAM model effectively assessed the effect of oceanographic parameters on skipjack tuna (Hidayat et al. 2019a) and small pelagic fish such as anchovies in the Bone Gulf (Safruddin et al. 2018).

Conclusion

This study concludes that the GAM statistical model has succeeded in explaining the effect of oceanographic parameters on the distribution of skipjack tuna in the Bone Gulf. This study also shows the vital role of oceanographic parameters in understanding the habitat of skipjack tuna related to its abundance and distribution in the waters. The distribution of skipjack tuna in the ocean shows a strong relationship with several parameters such as the SST, SSC, and water depth. Suitable or optimal conditions for skipjack tuna represented skipjack fishing areas during the study in the southeast monsoon period. Oceanographic parameters associated with fish catches correspond to the spatial and temporal distribution of skipjack tuna and have become a hot topic of discussion worldwide (Andrade 2003; Mugo et al. 2010; Zainuddin et al. 2019). From the results of this study, it can be suggested that management decisions to increase fishery yields need to consider oceanographic conditions and characteristics in the waters.

ACKNOWLEDGMENTS

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The use of statistical models in identifying skipjack tuna habitat characteristics during the Southeast Monsoon in the Bone Gulf, Indonesia

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Abstract. *Safruddin, Hidayat R, Farhum SA, Zainuddin M. 2022. The use of statistical models in identifying skipjack tuna habitat characteristics during the Southeast Monsoon in the Bone Gulf, Indonesia. Biodiversitas 23: xxxx.* Skipjack tuna (*Katsuwonus pelamis*) is the main fishery product in the Bone Gulf, Indonesia, since it has high economic value and is widely accepted by the market. The migration of skipjack tuna can be described by oceanographic dynamics, influenced by seasonal changes. This study aimed to explore the relationship between the oceanographic factors and the distribution and abundance of skipjack tuna obtained by pole and line fishing in the Bone Gulf, Indonesia. The research was conducted during the southeast monsoon season (April-September) from 2015 until 2018. Three oceanographic parameters were used to understand this relationship, i.e., Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), and water depth. Generalized Additive Models (GAMs) and Generalized Linear Models (GLMs) used to predict the spatial pattern of the skipjack tuna showed that all considered parameters significant influenced the distribution of skipjack tuna in the study area. The fish are mostly distributed from coastal to offshore areas, ranging between 50 to 2000 meters and even wider. The concentration tends to be high within the range of 29.5 to 30.5°C of SST, 0.25 to 0.35 mgm^{-3} of SSC, and 500 to 1500 meters of water depth. The research also found that the skipjack tuna migration to the Bone Gulf may have followed the current water interruption during the southeast monsoon, for preferred warmer temperatures and lower primary productivity waters in the offshore areas. This factor may represent the optimal habitat of skipjack tuna during the period and can be the basis for determining the skipjack fishing schedule in the Bone Gulf.

Keywords: Fishing schedule, oceanographic factors, satellite data, skipjack tuna habitat, southeast monsoon season

Abbreviations: Sea Surface Temperature (SST), Sea Surface Chlorophyll-a (SSC), Catch Per Unit Effort (CPUE), Generalized Additive Models (GAMs), Generalized Linear Models (GLMs), Akaike Information Criterion (AIC), Cumulative Deviance Explained (CDE)

INTRODUCTION

Skipjack tuna (*Katsuwonus pelamis*) is the most crucial target catch of marine fisheries in the world's oceans (Galland et al. 2016). Large schools of adult skipjack tuna are often associated with juvenile yellowfin (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) (IOTC 2020). Skipjack tuna is a highly migratory pelagic species inhabiting all tropical and subtropical waters (Artetxe-Arrate et al. 2020). However, they are found mainly in the tropical areas of the Atlantic, Indian, and Pacific Oceans, with the most incredible abundance seen near the equator. Since juvenile yellowfin and bigeye tuna often school with adult skipjack tuna, they are caught by purse seine and pole and line vessels whose main target is skipjack tuna (Hidayat et al. 2019; IOTC 2019; Safruddin et al. 2020).

The dynamics of oceanographic factors could affect the natural fluctuations in the distribution and abundance of skipjack tuna in the coastal and offshore areas (Mugo et al. 2010; Tseng et al. 2010; Wang et al. 2016). The distribution could also be influenced by the abundance of small pelagic fish such as anchovy in the same area (Safruddin et al. 2018). Therefore, there is an urgent need for information on the effects of oceanographic factors on skipjack tuna distribution (Andrade and Garcia 1999) to predict fishing ground potential zones for sustainable skipjack tuna fishery in the study area.

Statistical models such as generalized additive models (GAMs) and generalized linear models (GLMs) can be the most useful methods for determining the fish distribution in relation to oceanographic factors such as the sea surface temperature (SST), sea surface chlorophyll-a (SSC), and water depth (Safruddin 2013; Safruddin et al. 2018; Selao et al. 2019).

The Bone Gulf is one of the best skipjack tuna habitats in Indonesian waters (Zainuddin et al. 2020), with the peak fishing season lasting from early April until the end of September (southeast monsoon). Although skipjack tuna is an iconic species in the Bone Gulf, its local availability is a key factor for the pole and line fishery economy. However, there is a lack of information about its distribution, both spatially and temporally. Hence, this study is an attempt to investigate the availability of skipjack tuna caught using pole and line fishing gear under various oceanographic conditions and to discuss the oceanographic elements impacting skipjack tuna distribution by applying statistical models.

MATERIALS AND METHODS

Study area

The study area was located in the Bone Gulf (3-5°S) and (120-122°E), South Sulawesi, Indonesia (Figure 1). The field surveys used the pole and line method (local commercial fisheries) to investigate the fishing ground positions and the number of skipjack tuna catches during the study. Oceanography and bathymetric observations (satellite imagery data) were conducted monthly during the southeast monsoon (April-September) from 2015 until 2018. This study only focuses on fishing activities in the southeast monsoon, which is due to the peak season for skipjack fishing in the Bone Gulf takes place in the southeast monsoon.

Procedures

Data collection

In-situ data were obtained through a scientific survey at the fishing base at Murante fish landing site, Luwu district. We gathered the fishery data from 508 fishing ground positions. A global positioning system (GPS) was used to determine fishing ground coordinates (latitude and longitude). The in-situ field data consisted of the fishing position and catch per unit efforts (CPUEs). The oceanographic parameters (SST, and SSC) were obtained from satellite oceanography imagery data of high-resolution Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS), with a spatial resolution of 4 km, from 2015 until 2018 (April-September). The water depth data was gained from the ETOPO1 (Amante and Eakins 2009) satellite database. In this study, we used monthly temporal resolution. Furthermore, the SST and SSC averaged during southeast monsoon were mapped as shown in Figures 2 and 3, respectively.

Data analysis

To determine the effect of oceanographic parameters on horizontal distributions of skipjack tuna in the sea, statistical models (Hastie and Tibshirani 1990) were used for the CPUE and oceanographic datasets. The models, such as GAMs and GLMs, were created using the MGCV package in R-studio (Wood 2006) to predict the spatial patterns of skipjack tuna. The response variable used skipjack tuna catches (CPUE/fishing trip), and the predictor used oceanographic parameters (SST, SSC, and depth).

The hypothesized interactions between oceanographic parameters and skipjack tuna distribution are most likely non-linear. GAM was employed as an experimental technique to determine the forms of the associations. The connections between the skipjack distribution and each predictor (SST, SSC, and depth) were also determined. In a GLM, proper functions were utilized to identify these forms in the linear model, as indicated in Equations (1) and (2) (Safruddin 2013).

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (SSC) + s3\ (depth) + \varepsilon\ (GAM\ model) \quad (1)$$

$$g(\mu i) = \beta 0 + \beta 1\ (SST) + \beta 2\ (SSC) + \beta 3\ (depth) + \varepsilon\ (GLM\ model) \quad (2)$$

Where, g is the link function, μi is the expected value of the dependent variable for the presence of skipjack tuna (CPUE), α0 and β0 are the respective model's constant, sn is the predictor variable's smoothing function, ε is a random error term, and βn is the vector of model coefficients.

The Gaussian family with identical link functions was chosen since the skipjack tuna CPUE has a continuous distribution. Models were created from the ground up, with only one independent component such as SST, and predictor components were added later. Model selection was influenced by the predictor's significance, Akaike Information Criterion (AIC) reduction, and the deviance explained value. The best model was chosen from a group of seven to build the GAMs/GLMs. The GAMs/GLMs model was utilized to compare the results of the prediction models using a statistical criterion. They were also used to explain all observations with multiple variables, including inter-variable correlations (Safruddin 2013).

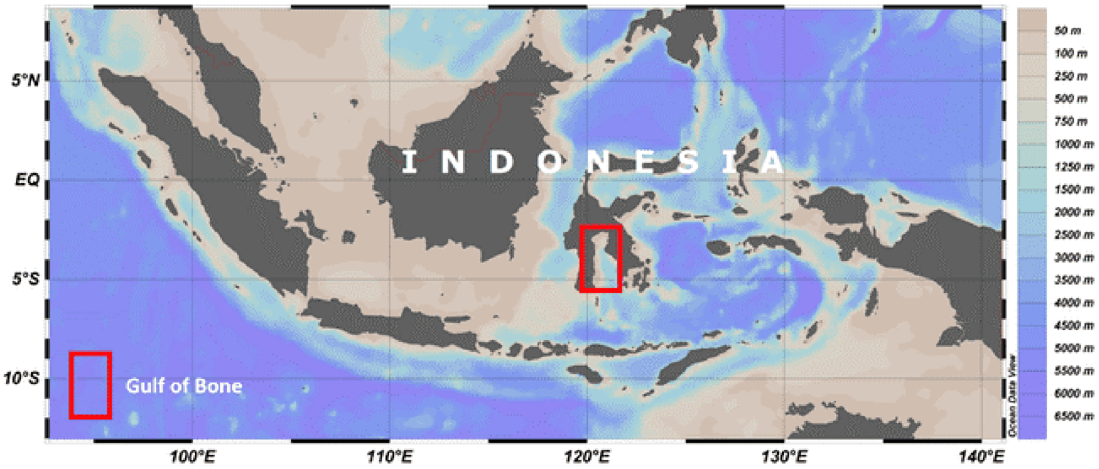

Figure 1. Map of the Indonesian seas with the red box representing the study area

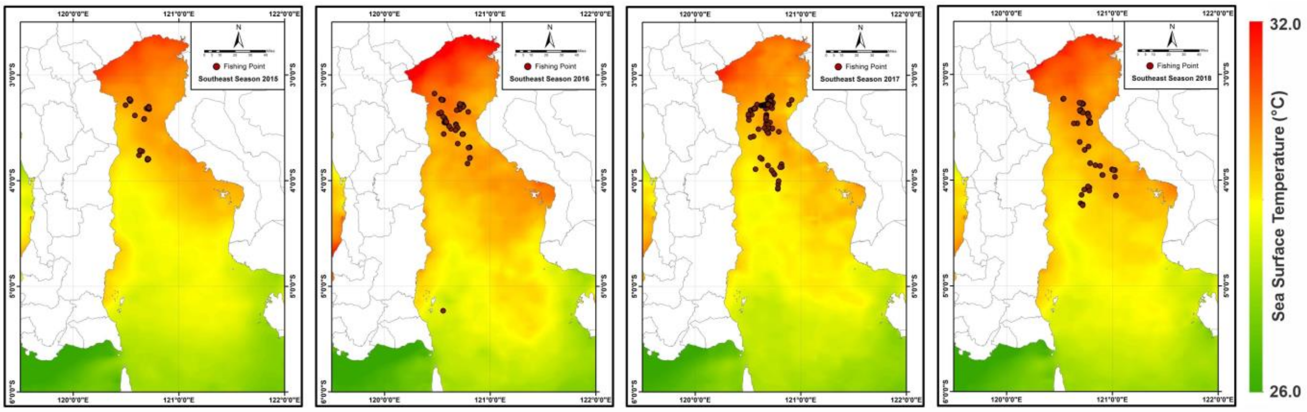

Figure 2. The profiles of SST average during southeast monsoon from 2015 until 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters. The gradient from green (low temperature) to red (high temperature) illustrates variations in SST in the waters. The red dot on the maps represents the location of the skipjack tuna fishing coordinates during the study

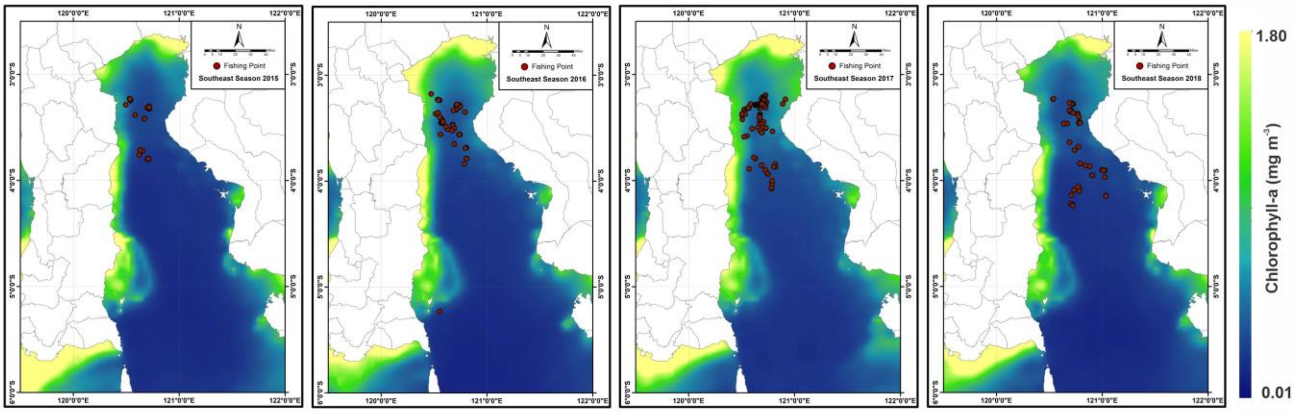

Figure 3. The profiles of SSC average during southeast monsoon from 2015 to 2018 overlaid with the skipjack tuna distribution in the Bone Gulf waters. The gradient from blue (low concentration) to yellow (high concentration) illustrates variations in SSC in the waters. The red dot on the maps represents the location of the skipjack tuna fishing coordinates during the study

RESULTS AND DISCUSSION

Skipjack tuna fishing ground

Skipjack tuna fishing grounds were mapped on latitude and longitude scales, with SST, SSC, and depth overlay (Figures 2-4). CPUE marks the position along the overlay in Figures 2-4, and each school is designated as a single point. Map contours with high SST, SSC, and depth, or the opposite, were also discovered.

The lowest SST and the highest SSC occur every year during the southeast monsoon period. The reverse happens in the northwest monsoon season, skipjack tuna was least abundant in the lower SST area (Figure 2) due to changes in water temperature caused by water currents from the Flores Sea entrance to the Bone Gulf. This could be a strategy in biological processes related to fish growth under changing oceanographic conditions. Skipjack tuna stock is positively correlated with oceanographic factors. It is distributed mainly in nearshore areas in the water depth range of 50 to 2000 m (Figure 4). The horizontal profiles of the SST and SSC structures for the 2015-2018 southeast monsoon season (Figures 2 and 3) are warmer near the coast than offshore. Skipjack schools occupy offshore areas where they prefer relatively higher SST and lower SSC (Figures 2 and 3).

The environmental conditions of skipjack tuna fishing grounds were used for four monthly datasets (April-August). As a result, the preference range suggested a possible association between all examined factors. For example, Figure 2 shows that skipjack tuna were found in temperatures ranging from 29.5 to 31.05°C. Likewise, the skipjack tuna schools concentrated in the narrow ranges of 0.15-1.00 mg.m^{-3} with respect to SSC (Figure 3). As for the depth of water, skipjack is found in waters with a depth of 50-2000 meters (Figure 4).

Effects of oceanographic factors on skipjack tuna distribution

The oceanographic conditions of the skipjack tuna schooling coordinates were employed in the current study for displaying the area and further analysis. Tables 1 and 2 show the models built using GAMs/GLMs on the skipjack tuna distribution scenarios utilizing predictor parameters (SST, SSC, and depth). Tables 1 and 2 present the results for each of the seven GAM and GLM models. Each model's predictor component(s) significantly affected the skipjack tuna distribution in p<0.05 reference levels, except depth as predictor two and three (Table 1). However, only SST substantially contributed to a single model predictor, two model predictors, and three model predictors in GLMs (Table 2). For the final model combination of SST, SSC, and depth, the cumulative deviance explained (CDE) was 21.9% (GAMs) and 12.830% (GLMs), respectively. Thus, Tables 1 and 2 suggest that the influence of oceanographic conditions may explain the fluctuation of skipjack tuna abundance distribution. Additionally, GAMs with higher CDE were well-suited to characterize the influence of oceanographic conditions on skipjack tuna distribution and abundance.

Tables 1 and 2 show the results of GAMs and GLMs, respectively. For both statistical models, the SST had the largest deviance explained among the single variable models. According to AIC (6048.045) and CDE (21.9%), and as the best model predictor of GAM, the combination of SST and SSC predicted relatively more significant variability in skipjack tuna catches. The AIC values for the three-parameter models were low (6049.831) and the most significant deviation explained was 21.9%. SST was the sole predictor model with the lowest AIC (6083.072) and the maximum CDE on the GLMs model (12.870%) and was also found as a combined two-parameter model between SST and SSC. The three-parameter models had the lowest AIC and the highest CDE overall (12.830%). All results produced by combining predictor factors at various levels revealed an increase or decrease in CDE and a higher AIC value of variation.

GAMs models were more effective than GLMs in understanding the effect of oceanographic factors on skipjack tuna distribution and abundance, as shown in Tables 1 and 2. The result of the GAM plots shows the impact of each predictor on schooling density of skipjack tuna as shown in Figures 5. The observed data points are represented by the rug plot on the horizontal axis, while the thin line shows the fitted function, and the grey shading represents the 95% confidence interval (Safruddin 2013).

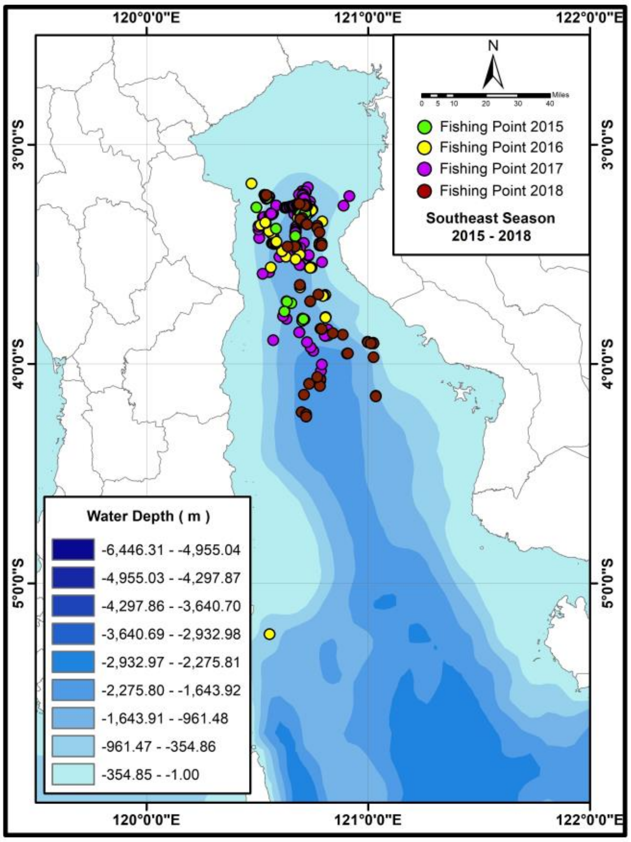

Figure 4. The profiles of bathymetric overlay with the skipjack tuna distribution during southeast monsoon from 2015 to 2018 in the Bone Gulf waters

Table 1. Oceanographic factor influences on the skipjack tuna distribution (n: 508), according to the GAMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<0.001 ***	6054.183	20.400
SSC	SSC	<0.001 ***	6121.052	8.400
Depth	Depth	<0.001 ***	6132.647	4.970
SST + SSC	SST	<0.001 ***	6048.045	21.900
	SSC	<0.001 ***		
SST + Depth	SST	<0.001 ***	6067.725	17.300
	Depth	0.296		
SSC + Depth	SSC	<0.001 ***	6121.672	8.350
	Depth	0.236		
SST + SSC + Depth	SST	<0.001 ***	6049.831	21.900
	SSC	<0.001 ***		
	Depth	0.832		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

Table 2. Oceanographic factor influences on the skipjack tuna distribution (n: 508), according to the GLMs models. Also included are the significant factor, AIC value, and CDE

Model	Oceanographic factor	P-*value*	AIC	CDE (%)
SST	SST	<0.001 ***	6083.072	12.960
SSC	SSC	0.894	6154.549	0.194
Depth	Depth	0.176	6152.724	0.165
SST + SSC	SST	<0.001 ***	6084.600	12.870
	SSC	0.494		
SST + Depth	SST	<0.001 ***	6084.987	12.800
	Depth	0.772		
SSC + Depth	SSC	0.385	6153.966	0.117
	Depth	0.109		
SST + SSC + Depth	SST	<0.001 ***	6085.819	12.830
	SSC	0.282		
	Depth	0.379		

Note: Sig. codes: 0.001 '***' 0.01 '**' 0.05 '*'

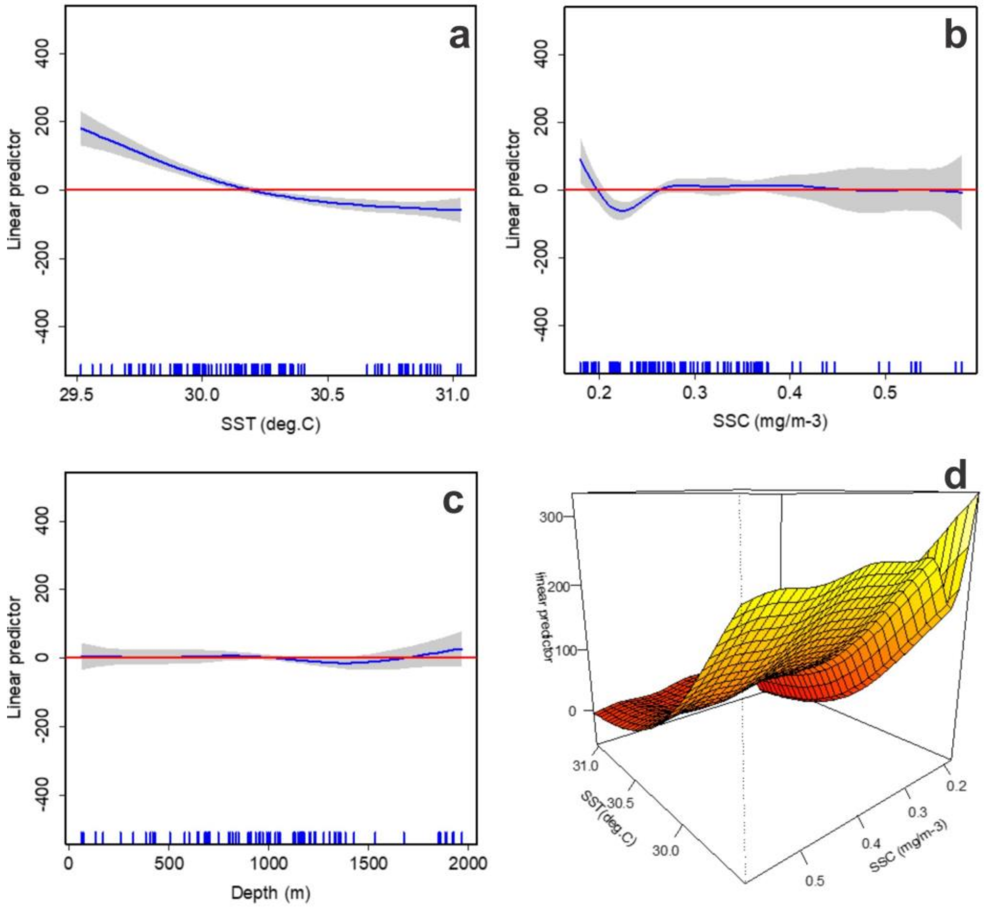

Figure 5. Skipjack tuna distribution responses of oceanographic factors; (a) SST, (b) SSC, (c) depth, and (d) best model predictor. The shaded area is the standard error indicating the 95% confidence interval. The stack of blue vertical lines on the x-axis indicates the density or distribution of the test parameter data. The y-axis is the partial effect of the variable, while the 3D graph depicts a combination model between significant SST and SSC to be the best predictive model

Figure 5 describes the impact of oceanographic conditions on skipjack tuna distribution. Around 29.5-30.5°C, the SST (Figure 5a) had a noticeable positive effect on skipjack tuna distribution. The confidence intervals are broader because there are fewer data points at 30.5-31.0°C. In the SSC plot (Figure 5b), there was a beneficial influence on school distribution in the SSC ranges of 0.25-0.35 mgm^{-3}. A consistent influence on skipjack tuna distribution was seen at a depth of 500-1500 m (Figure 5c). The study also found that models combining SST and SSC produced the most significant model prediction, with the lowest AIC and highest CDE (Figure 5d). Skipjack tuna distribution in the Northern Pacific Ocean near Japan waters had SST and SSC optimal values of 20.5-26°C and 0.3-0.37 mgm^{-3}, respectively, according to Mugo et al. (2010). The findings of this study corroborated those of

Zainuddin et al. (2017), who discovered that the distribution of skipjack tuna in the coastal area was primarily around 50 m depth.

Discussion

Oceanographic conditions such as the SST, which have the most significant impact on the growth stages of fish and their distribution (Yuniarti et al. 2013; Syah et al. 2020), play a main role in the natural oscillations of skipjack tuna stocks. As a result, SST is a great indicator for the fishing ground of skipjack tuna to have been used by fishermen and researchers for decades. Furthermore, changes in oceanic (physical and biological) parameters may significantly impact migration patterns and fish growth (Safruddin et al. 2018).

Since the SST in the research region may vary, measurements should be obtained frequently. More samples may be required to accomplish this goal. Therefore, one of the objectives of this research was to determine how oceanographic data can be used in research (e.g., correlation between skipjack tuna distribution and abundance). Temperature fluctuations are often linked to the biological richness (Iskandar et al. 2017; Takarina et al. 2018), such as anchovy distribution and abundance as the prey for skipjack tuna, and they have an important influence on fish physiology (Kunarso et al. 2011; Olson et al. 2016; Duffy et al. 2017).

Satellite remote sensing imagery directly provides horizontal and large-area information on oceanographic conditions, which may be utilized to understand oceanographic processes in the surface water better. The combination of satellite data with acoustic technology will, of course, increase the accuracy of the data. For example, CTD and satellite data are combined when conducting data observations (Safruddin 2013). As a result, four-year datasets of oceanographic conditions (SST, SSC, and water depth) on skipjack tuna position were employed, with scattered plots and optimal ranges indicating a possible association among all variables observed, as shown in Figure 5.

Skipjack tuna can be found in coastal areas, sometimes in large numbers, especially in upwelling areas (Sari et al. 2018; Wijaya et al. 2020). This study details the interactions between skipjack tuna and its oceanographic variables taking into account temporal and spatial scale aspects to understand the various processes involved and how they can be used to model dynamics and estimate their abundance (Prista et al. 2011; Selvaraj et al. 2020). The catch data used is the distribution of catches in Bone Bay. Although spatially, several fishing points are located in almost the same area, the dynamics of different oceanographic parameters each year make the description of the range of SST and SSC at each skipjack fishing point experience different.

Oceanographic conditions are essential variables to assess the abundance of fish in the waters, especially skipjack tuna, representing the original habitats. The distribution of skipjack tuna observed during the daytime is closely related to the dynamics of oceanographic variables and fishing operations in the Bone Gulf. As shown in Tables 1 and 2 and Figure 5, the effect of oceanographic parameters on the abundance and distribution of skipjack tuna is also a reference for water depths. The p-value, AIC, and CDE can all be used to assess the impact of changing oceanographic conditions on skipjack tuna CPUE. As a result, oceanographic variables connected to skipjack tuna distribution are critical for understanding skipjack tuna habitat preferences.

Oceanographic phenomena in the waters, such as frontal oceanic zones, eddies, and upwelling areas, often occur with different characteristics as seen in the Bone Gulf and the Flores Sea (Zainuddin et al. 2017, 2019; Hidayat and Zainuddin 2019; Hidayat et al. 2019b). This event makes the waters very dynamic and affects the horizontal distribution of fish in the Bone Gulf. The dynamic oceanographic parameters in this area produce highly productive habitats and serve as foraging grounds for various commercially and ecologically important species such as anchovies and skipjack tuna (Safruddin et al 2018; Hidayat et al 2019b)

The results of this study indicate that the SST tolerance value for skipjack tuna is in the range of 29.5-30.5°C and in the range of 0.25-0.35 mgm^{-3} for SSC parameters (Figures 5a and 5b). However, in addition to SST and SSC, Indonesian Throughflow (ITF) and Asian monsoons also influence the location of the optimum habitat for skipjack tuna (Gordon 2005). Changes in the value of SST in the waters are heavily influenced by the seasonal cycle, in contrast to the SSC, which is not influenced much by the seasonal cycle. Therefore, the migration of skipjack tuna in the northern waters of the Bone Gulf is thought to have followed the mass movement of water in the southeast monsoon, occupying relatively warm areas in offshore waters.

Based on the lowest AIC value and the highest CDE, the GAM nonlinear model is the best statistical model to understand the effect of oceanographic parameters on the distribution and abundance of skipjack tuna. This study is also supported by previous findings in the Makassar Strait, which reported that the GAM model effectively assessed the effect of oceanographic parameters on skipjack tuna (Hidayat et al. 2019a) and small pelagic fish such as anchovies in the Bone Gulf (Safruddin et al. 2018).

This study concludes that the GAM statistical model has succeeded in explaining the effect of oceanographic parameters on the distribution of skipjack tuna in the Bone Gulf. This study also shows the vital role of oceanographic parameters in understanding the habitat of skipjack tuna related to its abundance and distribution in the waters. The distribution of skipjack tuna in the ocean shows a strong relationship with several parameters such as the SST, SSC, and water depth. Suitable or optimal conditions for skipjack tuna represented skipjack fishing areas during the study in the southeast monsoon period. Oceanographic parameters associated with fish catches correspond to the spatial and temporal distribution of skipjack tuna and have become a hot topic of discussion worldwide (Andrade 2003; Mugo et al. 2010; Zainuddin et al. 2019). From the results of this study, it can be suggested that management decisions to increase fishery yields need to consider oceanographic conditions and characteristics in the waters.

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