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Assessing the Impact of the 2020 – 2021 La Niña Event on Longtail Tuna (*Thunnus tonggol*) Migration Patterns Using MaxEnt Modeling

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ABSTRACT

Thunnus tonggol is a primary target in commercial capture fisheries. The Makassar Strait region is defined by diverse physical processes and climatic influences, notably the El Niño Southern Oscillation (ENSO). This study aimed to identify the migration patterns of the longtail tuna that La Niña influenced in 2020/2021 and to forecast fishery regions using the MaxEnt model. The data utilized includes satellite image data of SST, chl-a, SSH, salinity, and current speed, as well as data on the presence of the longtail tuna. During the peak phase of La Niña, the highest CPUE was recorded, with an average of 450kg/ trip. The MaxEnt model suggests that the optimal sea surface temperature for the longtail tuna is between 29 and 30°C. The longtail tuna typically have an ideal chlorophyll-a level of 0 to 0.3mg/ m^3. The ideal SSH, salinity, and current velocity values are 0.63 - 0.64m, 33 - 33.5ppt, and 0.1 - 0.3m/ s, respectively. SSH is the key parameter element influencing the longtail tuna distribution. The HSI maps show that the distribution of longtail luna migrates northward at the end of the La Niña period, roughly in coordinates 3 - 5° S and 114 - 118° E.

INTRODUCTION

As an oceanodromous pelagic fish, the longtail tuna *(Thunnus tonggol)* is often found in neritic waters of tropical and subtropical regions between 47º N - 31º S and 34° E - 154º E **(Froese & Pauly, 2009)**. Eight tuna species belonging to the genus *Thunnus* accounted for a global catch of 5.4 million metric tons, representing approximately 7.9% of the total marine fish harvest worldwide **(FAO, 2019)**. One of the species that is the main target in commercial capture fisheries is *Thunnus tonggol* (Bleeker, 1851). As reported by **FAO (2024)**, recent estimates of Indonesian fisheries from 2017 to 2021 show an upward trend in the catch rate of *T. tonggol* within Indonesian waters. In 2017, the production was 106.300 tons, and increased to 208.179 tons in 2021.

Oceanographic conditions play a critical role in shaping the abundance and spatial distribution of fish populations **(Mugo *et al.*, 2010; Sartimbul *et al.*, 2010)**. Oceanographic dynamics, which lead to constant changes in fishing areas, present obstacles for fishermen in their fishing endeavors. Therefore, one of the efforts in managing capture fisheries is to regularly and repeatedly study the impacts of oceanographic parameters on fish catches **(Tangke, 2020; Zainuddin *et al.*, 2023a)**.

The sea surface temperature in Indonesia and its surrounding waters fluctuates both on a daily basis and over longer monthly timescales. This temperature alteration results in forming a distinct type of water mass **(Purba *et al.*, 2020)**. The average SST in Indonesian waters is 28.08°C, ranging from 21.79 to 31.05°C **(Qu *et al.*, 2005)**. The correlation between spawning activity and sea surface temperature (SST) is a common characteristic of all tuna species, as they are repetitive broadcast spawners that require extremely high lifetime fecundity to ensure reproductive success. This relationship exists because SST must generally exceed approximately 24°C for spawning to occur **(Kusuma *et al.*, 2017)**. The average salinity in Indonesia fluctuates between 33 and 35 psu **(Purba *et al.*, 2024)**. This salinity pattern is critical for marine life, particularly tuna species, which require a salinity range of approximately 33 to 36 psu for maximum physiological performance **(Semedi *et al.*, 2023; Syamsuddin *et al.*, 2024)**.

Geographically, the Makassar Strait lies between Kalimantan to the west and Sulawesi to the east, forming a direct connection to the Pacific Ocean in the north and linking to the Java Sea and Flores Sea in the south **(Pratiwi, 2018)**. A basin divides the strait into northern and southern regions, influencing the strong southward movement of the Indonesian Throughflow (ITF) **(Mayer & Damm, 2012)**. The Makassar Strait to the Java Sea region is influenced by a range of physical processes and climatic factors, such as the monsoon and the El Niño Southern Oscillation (ENSO), which exert a significant influence on the spatial configuration and temporal variability of the system **(Gaol & Sadhotomo, 2017)**.

Fishing activities are concentrated in the southern and central parts of the strait, especially near the waters off South Sulawesi and East Kalimantan. Several studies and fisheries reports indicate that tuna are commonly caught using handline, pole-and-line, and purse-seine methods. The towns of Makassar, Parepare, and Kendari are notable landing sites on the Sulawesi side. At the same time, coastal areas of East Kalimantan, such as Balikpapan and Tarakan, also contribute significantly to tuna production **(Amir & Mallawa, 2015)**.

Investigating the impact of climate change on fish communities' responses has become an essential focus for elucidating the intricate dynamics of marine ecosystems. The El Niño Southern Oscillation (ENSO) is a principal factor influencing interannual climate variation, characterized by alternating El Niño (warm-phase) and La Niña (coldphase) episodes **(Liu *et al.*, 2025)**. ENSO affects various industries, including both aquaculture and capture fisheries, as well as marine ecosystems. The alterations in aquatic environmental conditions driven by ENSO events in Indonesia are likely to have considerable consequences for fish resources **(Lehodey *et al.*, 2020; Suhermat *et al.*, 2022)**.

La Niña is a large-scale meteorological circumstance characterized by below-average SST in the central and eastern equatorial Pacific, which profoundly affects global oceanographic conditions **(Abish *et al.*, 2018)**. In Southeast Asia, particularly Indonesia, La Niña occurrences frequently result in heightened precipitation and alterations in sea surface temperatures and ocean currents **(Bolan *et al.*, 2024)**. These environmental changes can significantly impact marine ecosystems, modifying the availability and distribution of nutrients in the water. Consequently, fish species may alter their migratory patterns, spawning behaviors, and habitat preferences in reaction to the changed conditions.

Remote sensing has been implemented in numerous investigations to optimize fisheries potential. As highlighted by **Solanki *et al.* (2016)** and **Purwandari *et al.* (2019)**, the most practical alternatives for detecting and mapping changes in spatial and temporal oceanographic parameters is remote sensing. The Maximum Entropy (MaxEnt) model is foremost models being developed to estimate marine fishery areas using remote sensing technology **(Silubun *et al.*, 2015; Gustantia *et al.*, 2021)**. This study aimed to discover longtail tuna migration patterns influenced by La Niña and to predict fishing regions. Predicting fish catchment areas improves fishery management and maximizes catch productivity.

MATERIALS AND METHODS

1. Study area

The field site was situated in the Makassar Strait region identified by coordinates 1° N – 5° S and 115° E – 121° E. Fig. (1) illustrates the selection of the region based on ocean dynamics due to its strategic location as path of the entry for the ITF.

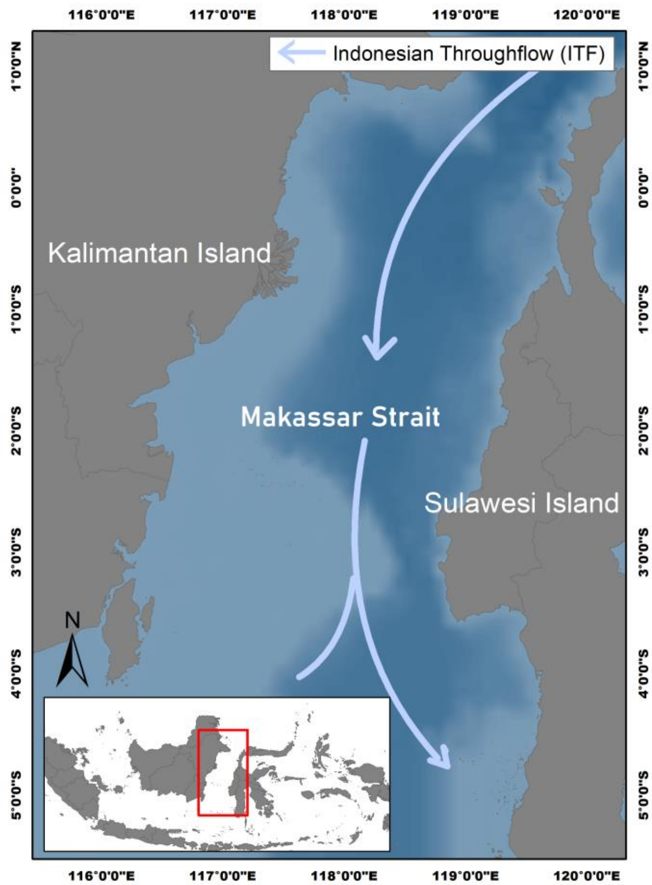


Fig. 1. A study area map of the Makassar Strait

The water characteristics of the 0° latitude area, which includes the MS, are influenced by a variety of parameters, including the monsoon, relative sea-level change, and regional wind **(Purba *et al.*, 2021)**. The Makassar Straits' connection to the Pacific Ocean directly influences the oceanographic characteristics, as it is part of the Pacific Western Equatorial Current System. The Makassar Strait, functioning as the westerly route of the ITF, facilitates the movement of water from the North Pacific to the Lombok Strait and the Banda Sea through the Flores Sea, with a sill depth of 680m **(Gordon *et al.*, 2019)**.

Due to its location between the continents of Asia and Australia, the Makassar Strait is dominated by the Indonesian monsoon current system and the Indonesian Throughflow (ITF) as the two main current systems **(Noorsyoda *et al.*, 2023)**. The Indonesian monsoon current system is driven by seasonal wind variations, while the Indonesian Throughflow (ITF) is a thermohaline current that plays a significant role in influencing global climate patterns **(Sprintall & Revelard, 2014; Atmadipoera *et al.*, 2016; Naulita, 2016)**.

2. Data

2.1 Satellite-derived oceanography data

Oceanographic characteristics estimated from satellite data were employed to ascertain the habitat distribution of longtail tuna *(Thunnus tonggol)* during the 2020–2021 La Niña period. The website https://oceancolor.gsfc.nasa.gov/ was used to obtain oceanographic variables, such as chlorophyll-a concentration and sea surface temperature (SST). Data were collected monthly with a spatial definition of 4km. The website https://marine.copernicus.eu/ provided data on salinity, sea surface height (SSH), and current direction and speed at a monthly temporal resolution and a spatial resolution of 9km. These data have been widely used in modeling fishing grounds, particularly through the application of the MaxEnt model, as confirmed in several studies by **Suhermat *et al.* (2022)**, **Nurani *et al.* (2024)** and **Syamsuddin *et al.* (2024)**. To modify the habitat model analysis, each oceanographic variable was resampled to a spatial resolution of 9km. Parameter data were averaged every three months following the La Niña period, which encompassed the onset (July–Sept 2020), peak (Oct–Dec 2020), and end phase (Apr–June 2021). Table (1) contains information regarding oceanographic data parameters.

Table 1. Overview of oceanographic parameter specifications for habitat model analysis

Parameter	Sensor	Resolution		Sources
		Temporal	Spatial	
SST	AquaMODIS	Monthly	4 km	oceancolor.gsfc.nasa.gov
Chlorophyll-a	AquaMODIS	Monthly	4 km	oceancolor.gsfc.nasa.gov
Salinity	CMES	Monthly	9 km	marine.copernicus.eu
SSH	CMES	Monthly	9 km	marine.copernicus.eu
Current	CMES	Monthly	9 km	marine.copernicus.eu

Satellite imagery data were subsequently transformed from raster (.nc) to ASCII (.asc) format utilizing ArcGIS 10.8. The acquired raster data were later modified to align with the extent of the environmental layers, utilizing the “extract by mask” tool, in accordance with the study area. The data in the cell size column was resampled to 9km or

0.083°. The “Raster to ASCII” tool was utilized for the conversion of raster to ASCII format.

2.2 Longtail tuna (T. tonggol) occurrence data

Data on the occurrence of longtail tuna (*Thunnus tonggol*) were obtained from the logbooks of the Ministry of Marine Affairs and Fisheries and the Nizam Zachman Ocean Fishing Port. The recorded data included the date of capture, fish species, fish weight, and geographical coordinates (latitude and longitude). The data, encoded in .csv format, were filtered to include only fish species, latitude, and longitude. To determine the average catch per unit effort (CPUE) over three-month intervals during the 2020–2021 La Niña phase, CPUE was calculated using the following formula:

$$CPUE = \frac{Catch}{Effort}$$

(Listiani *et al.*, 2017):

Where:
CPUE = catch per fishing effort (kg/trip)
Catch = catch on year t (kg)
Effort = fishing effort in year t (trip)

2.3 Methods

2.3.1 Maximum entropy (MaxEnt) model construction

The environmental layer is represented by oceanographic parameter data, while catch production data represent the sample data. The model is built with default parameters, which include a random test percentage of 20, a maximum iteration number of 500 (convergence), and 10.000 background points **(Fourcade *et al.*, 2014)**. Regularization techniques utilize background data points to reduce the likelihood of overfitting the model. Convergence is implemented to reduce ambiguity in prediction, while the random test percentage is implemented to evaluate model performance and reduce bias. The receiver operating characteristic (ROC) area under the curve (AUC) value will be employed to assess the prediction model that has been developed**.**

To obtain alternative estimates of the most important variables in the model, "Do jackknife test to measure the variable important" command. The Jackknife test was developed to determine the impact of environmental variables in predictive modeling **(Phillips, 2010; Yang *et al.*, 2012)**. The AUC value is a numerical scale that ranges from 0 to 1. A prospective region with a value of 1 is considered to have perfect discrimination, while a value of 0.5 indicates predictive discrimination that is equivalent to random discrimination. A value less than 0.5 suggests that the model's performance is inferior to that of random processes. The AUC metric quantifies the capacity of a model to differentiate between locations where species are present and locations where species are absent. The model with the highest AUC value is the most suitable for identifying prospective tuna habitat.

RESULTS AND DISCUSSION

1. ONI index

Fig. (2) displays the ONI Index overlaid with longtail tuna CPUE, which summarizes the SST anomalies observed from 2020 to 2021. It focuses on the La Niña phase and its impact on the CPUE. In general, catch per unit effort (CPUE) tends to exhibit variability in response to SST anomalies during La Niña events, with notably elevated CPUE values typically observed during periods of strong La Niña conditions.

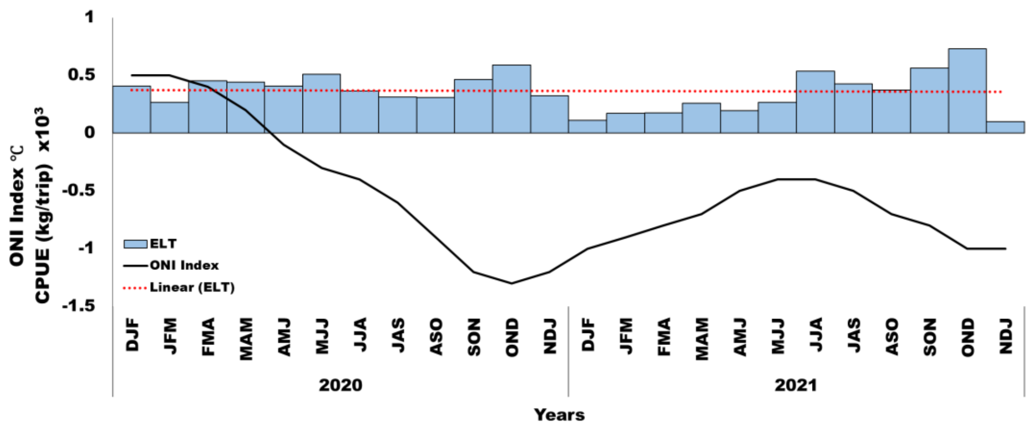


Fig. 2. ONI Index (source: NOAA) overlaid with longtail tuna CPUE from 2020 to 2021

The ONI index indicates that the La Niña phase persisted from 2020 to 2021. According to the Indonesian Agency for Meteorology, Climatology, and Geophysics, the year 2020/2021 experienced a Moderate La Niña phenomenon. According to the Niño 3.4 index data from the National Oceanic and Atmospheric Administration (NOAA) (Fig. 2), La Niña commenced during the JAS period (July-September) and intensified in the OND period (October-December) before concluding in the AMJ period (April-June). This is the basis for the spatio-temporal visualization of oceanography, CPUE of longtail tuna, and forecasts of migration patterns based on the subsequent HSI. The CPUE number is divided by 1000 to align it with the ONI index. The graph indicates that during the onset of the La Niña phase in JAS 2020, characterized by an SST anomaly of -0.6, the CPUE experienced a decline relative to the preceding month during the neutral phase, namely 313kg/ trip. The CPUE value persisted in its ascent as the La Niña phase intensified. During the zenith of La Niña, characterized by a sea surface temperature anomaly of -1.3 (OND 2020), the catch per unit effort was recorded at 590 kg/trip. At the onset of 2021, the average catch per unit effort (CPUE) exhibited a general decline. After the La Niña phase, when the sea surface temperature anomaly was -0.5, the average catch per unit effort recorded was 192kg/ trip, representing the lowest value.

3.2 Average CPUE during the La Niña phase

Fig. (3) depicts the average CPUE per three months during the start phase of La Niña (July-September 2020), peak La Niña (October-December 2020), and end phase of La Niña (April-June 2021). In general, the highest CPUE values were recorded during the strong La Niña phase, specifically in the October–December (OND) 2020 period.

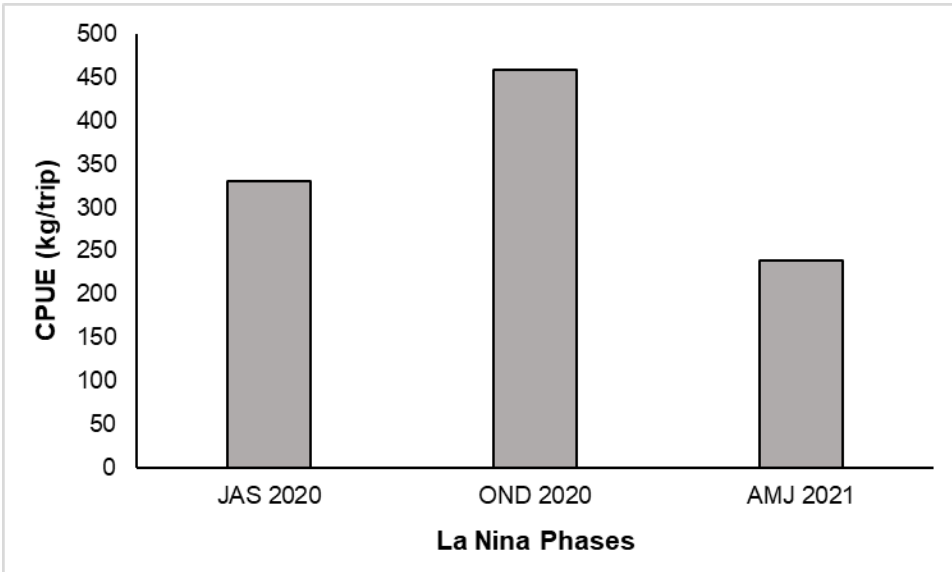


Fig. 3. Average CPUE during 2020-2021 La Niña Phases Overlaid with ONI Index

The graph illustrates that the highest average catch per unit effort (CPUE) occurs during the peak phase of La Niña, reaching an average of 459 kg per trip. In contrast, the early stage of La Niña results in an average CPUE of 329 kg per trip. The lowest CPUE, recorded at 239 kg per trip, is observed during the final phase of La Niña.

3.3 Variability of oceanographic parameters during the La Niña phase

This section explores the variability of oceanographic parameters within the Makassar Strait to highlight key patterns of the La Niña and its effect on longtail tuna distribution. The variability of oceanographic parameters overlaid with longtail tuna fishing location and CPUE is depicted in Fig. (4).

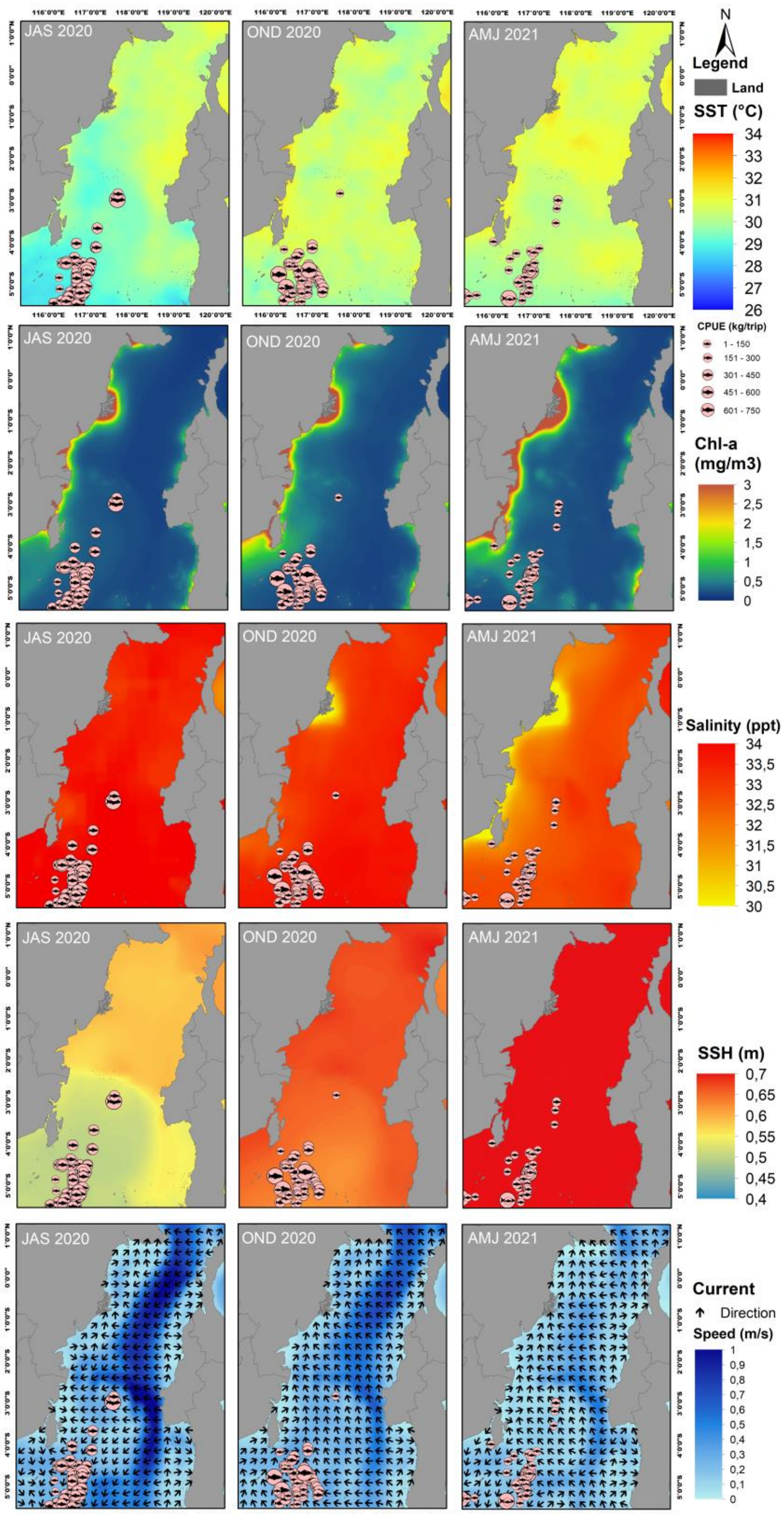


Fig. 4. Variability of oceanographic parameters per three months during the La Niña phase overlaid with longtail tuna CPUE, from top to bottom in order: a) SST, b) Chl-a, c) salinity, d) SSH, and e) current speed

SSTs are typically low at the onset of the La Niña phase (JAS 2020), particularly in the southern region of the Makassar Strait, with a range of 29–30°C. Conversely, the northern region experiences higher SSTs, ranging from 30–31°C. SST then continued to rise from OND 2020 to AMJ 2021, ranging from 30 to 31°C. Typically, the increase in SST takes place from November to May. In the interim, the SST began to decline in June, and the lowest apogee was observed in August **(Baharuddin *et al.*, 2022)**. Solar radiation becomes more effective in April due to the seasonal wind speed, resulting in elevated sea surface temperatures **(Zulkhasyni *et al.*, 2015)**. The regional and temporal variations of Indonesia's SST can be influenced by the Indonesian Throughflow, climate change caused by ENSO and IOD, and monsoon winds **(Hidayat *et al.*, 2016; Martono, 2016)**. In JAS, chlorophyll-a exhibits a distribution and concentration that progressively increases from low to high, with a range of 0 to 0.5mg/ m^3 and 0.5 to 1mg/ m^3 in AMJ, similar to SST. Longtail tuna are typically found in moderately warm sea surface temperatures, ranging from 29°C during July–September (with catch rates between 151–750 kg/trip) to around 30°C in October–December and April–June (with catch rates between 1–450 kg/trip). Additionally, their presence is associated with low chlorophyll-a concentrations, generally between 0 and 0.5mg/ m^3.

Conversely, salinity commences with a high distribution in JAS, which spans from 33.5 to 34ppt, and diminishes in OND, with a range of 32 to 33ppt. During the late La Niña period, the salinity concentration and distribution are at their lowest, with a range of 31 to 32ppt. Low salinity concentrations are also observed in the coastal regions of Kalimantan Island. Elevated salinity levels are associated with the occurrence of longtail tuna, which tend to correlate with salinity ranging from 32 to 33ppt, accompanied by a wide range of CPUE values (1–750kg/ trip). In JAS, SSH is at a low value, and there are discrepancies in values between the northern (0.6 - 0.65m) and southern (0.5 - 0.65m) regions of the Makassar Strait. In the July–September period, higher CPUE (151–750kg/ trip) was observed at sea surface heights (SSH) between 0.5 and 0.55 meters. However, CPUE generally declined with increasing SSH. In the early La Niña phase, the current speed is considered high (0.8 - 1m/ s), particularly the ITF pattern, which is marked in dark blue. This is inversely proportional to the current speed. The current pace in AMJ is decreasing in conjunction with the conclusion of the La Niña phase, with a range of 0.1 to 0.4m/ s. It is also evident that the ITF path becomes dim and nearly invisible. Additionally, longtail tuna are typically distributed in areas characterized by low current speeds.

3.4 MaxEnt model performances

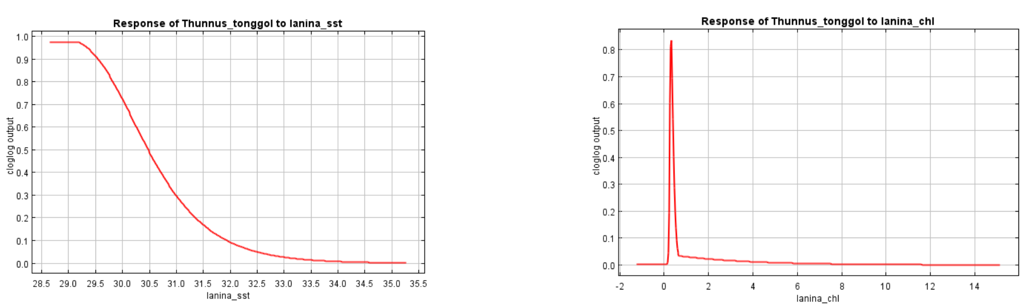
The MaxEnt model was formed using five oceanographic parameters to determine the migration pattern and the effect of La Niña on the distribution of longtail tuna in the Makassar Strait.

Table 2. Percentage distribution of oceanographic parameters for longtail tuna based on the MaxEnt model construction

Parameter	Percent Contribution (%)
Sea Surface Height	40.1
Current	23.9
Sea Surface Temperature	22.4
Chlorophyll-a	11.4
Sea Surface Salinity	2.2

The distribution of longtail tuna is most significantly influenced by SSH, which accounts for 40.1%. This outcome is succeeded by current speed (23.9%), SST (22.4%), and chlorophyll-a (11.4%). In contrast, salinity is the parameter that contributes the least, with a value of 2.2%. This is consistent with the findings of **Syamsuddin *et al.* (2024)**, who discovered that SSH is the most important characteristic for the existence of skipjack tuna. Higher SSH values in skipjack tuna habitats correlate with increasing skipjack rates **(Surahman, 2016; Hsu *et al.*, 2021)**.

The dynamics of atmospheric-oceanic interactions, including the El Niño Southern Oscillation (ENSO) in the Pacific Ocean **(Dwi Susanto *et al.*, 2012)**, significantly affect the volume of water transport through the Makassar Strait, which is observed to increase during the La Niña phase. Currents influence the movement and distribution of marine biodiversity, including tuna **(Rivai *et al.*, 2018)**. SST and chlorophyll-a are factors that are often used to explain spatial patterns and the size of fish populations based on the catch-per-unit effort (CPUE) method **(Chassot *et al.*, 2011; Kamaruzzaman & Mustapha, 2023)**. Meanwhile, the distribution and concentration of salinity in each phase are nearly identical, making salinity the characteristic with the least contribution to longtail tuna.



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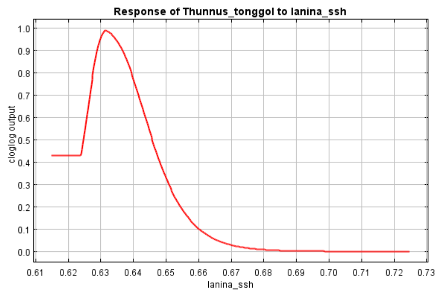

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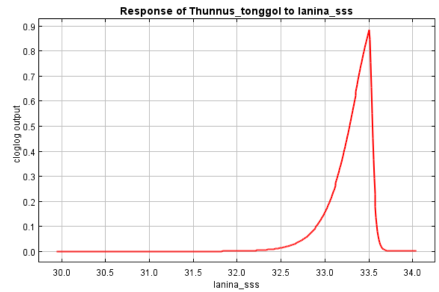

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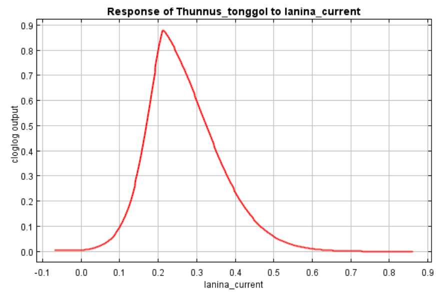


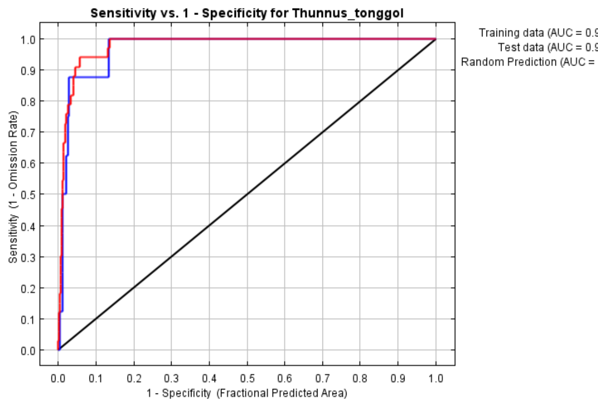
(e)

Fig. 5. Response curve of the ideal oceanographic parameters for longtail tuna, a) SST, b) Chl-a, c) SSH, d) SSS, and e) current speed

Based on the response curve graph, the optimal SST for the longtail tuna ranges between 29 - 30°C. This finding is consistent with the study carried out by **Puspita *et al.* (2023)**, which reported that the optimal SST for other tuna species falls within the range of 29 to 30°C. Furthermore, the ideal chlorophyll-a concentration for longtail tuna tends to be low, with a range of 0 - 0.3mg/ m^3. The ideal range for SSH, salinity, and current velocity is 0.63 - 0.64m, 33 - 33.5ppt, and current velocity 0.1 - 0.3m/ s, respectively. This parallels the findings of **Syamsuddin *et al.* (2023)**, which indicate that oceanic conditions within this range during La Niña yield elevated catches.

3.4 Performance of the MaxEnt model in determining longtail tuna habitat based on the La Niña phases

The response curve demonstrates robust and consistent values in each phase, exceeding 0.9. An AUC score that surpasses 0.80 indicates that the regional base model has good to exceptional suitability (Fig. 6).



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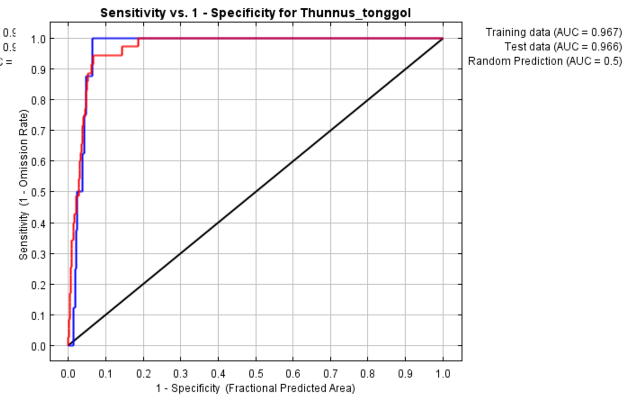

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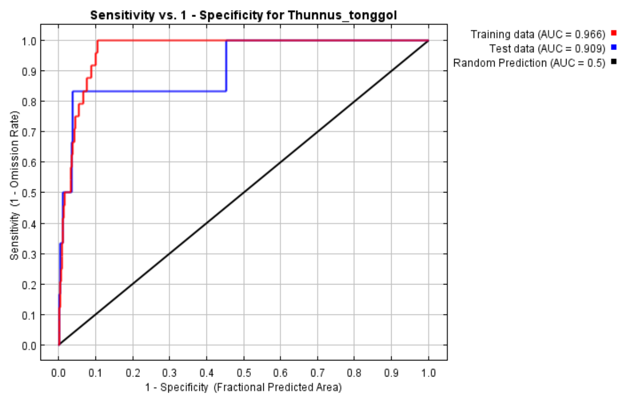

(c)

Fig. 6. ROC Curve a) JAS 2020, b) OND 2020, and c) AMJ 2021

All La Niña phases exhibit AUC values exceeding 0.9, with a progressive decline from the early to the late stages, recording AUCs of 0.978 (JAS), 0.967 (OND), and 0.966 (AMJ), respectively. **Phillips *et al.* (2004)** assert that Maxent employs an efficient penalty function (i.e., regularization) in parameter estimation to mitigate overfitting. Regularization exerts the most significant impact when the sample size is constrained, facilitating more precise predictions in these scenarios.

The Jackknife test is used to asses the influence of environmental variables on the model. To determine the effect of each environmental variable during the model-building process, the jackknife test was applied. The blue bar chart displays the contribution of each environmental variable to the AUC value. The tosca bar chart shows the contribution of environmental variables when they are excluded from the model. Lastly, the red bar chart highlights the impact of each variable on the probability of longtail tuna presence.

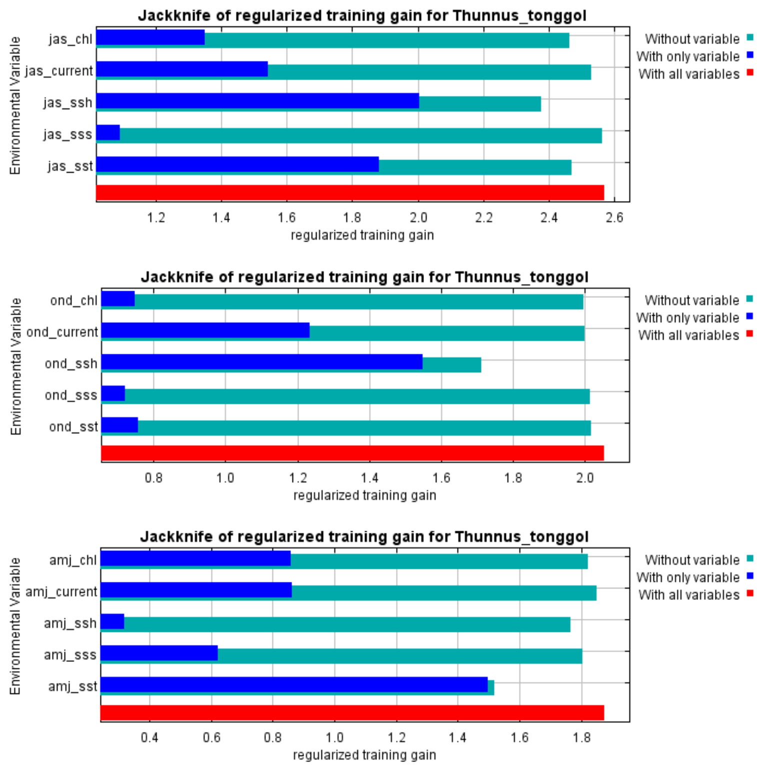

Fig. 7. Jackknife test with five parameters, from top to bottom in order: a) JAS 2020, b) OND 2020, and c) AMJ 2021. The dark blue bars illustrate the test gain when a variable is omitted, aiding the identification of variables that substantially influence the model's performance. The light blue bars illustrate the test gain achieved by utilizing the specified variable alone, emphasizing its distinct predictive capability

The jackknife test indicates that SSH is the most significant parameter from the early period (JAS) to the peak of La Niña (OND). Nonetheless, the distinction is evident in the final phase (AMJ), where SST emerges as the paramount characteristic. According to the tosca bar jackknife test, SST is a significant metric in isolation, although its overall effect is quite minimal. This is due to the strong correlation of SST with other variables. Several empirical studies, including those conducted by **Ranintyari *et al.* (2018)** and **Tussadiah *et al.* (2019**), reveal that SST is critical and its variations have an impact on fish survival. Simultaneously, SSH significantly enhances and exhibits a substantial gain on the jackknife, rendering this parameter consistent. The Maximum Entropy Model generates prediction maps based on numerous analyses, as shown in Fig. (8).

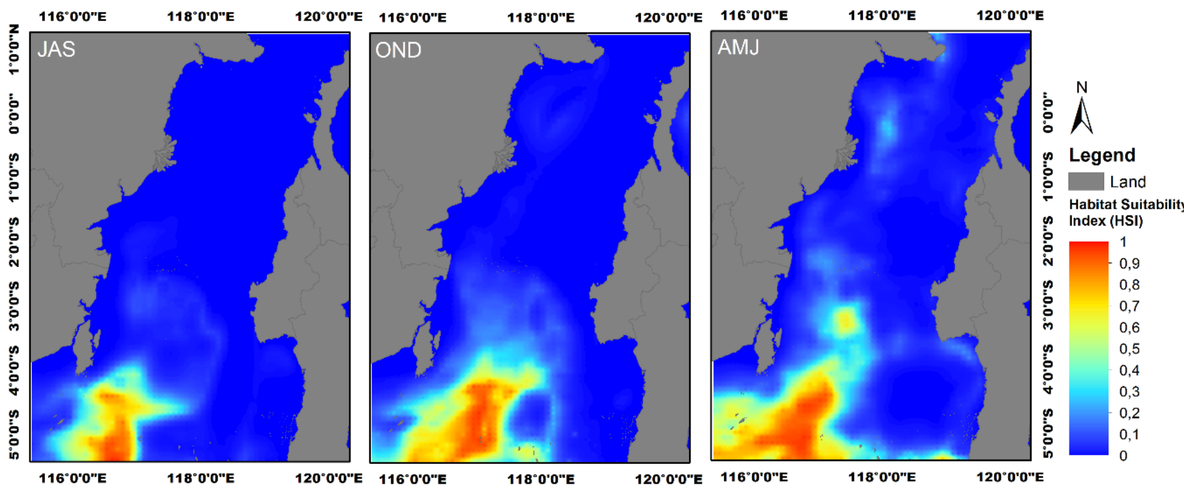

Fig. 8. Habitat suitability index (HSI) prediction map for longtail tuna based on La Niña phases

The MaxEnt model results on JAS show that the HSI zone is limited, with coordinates of 4 - 5° S and 114 - 116° E. This region expands in OND, specifically at 4 - 5° S and 114 - 118° E. The highest and widest HSI occurs during La Niña 's final phase, around coordinates 3 - 5° S and 114 - 118° E. This shows that the distribution of longtail luna will shift northward once the La Niña phase ends. The regional distribution of the habitat suitability index (HSI) for longtail tuna indicates a distinct northward expansion during the La Niña phase. In the initial phase (JAS), areas of high adaptability were predominantly located in the southern region. As the La Niña event advanced (OND), these favorable habitats began to migrate northward, and by the subsequent phase (AMJ), elevated HSI values expanded farther north.

This pattern indicates a significant impact of La Niña-induced oceanographic alterations on the distribution of longtail tuna, presumably influenced by variations in sea surface height, current speed, and sea surface temperature dynamics. Regional and global climate change influences oceanographic parameters, which in turn affect the distribution and availability of fish **(Simbolon, 2019)**. **Syamsuddin *et al.* (2024)** assert that oceanic factors significantly influence spatial alterations in distribution and migration patterns.

CONCLUSION

The maximum CPUE was recorded during the peak phase of La Niña, averaging 450kg per trip. The MaxEnt model suggests that the optimal sea surface temperature (SST) for the longtail tuna ranges between 29 and 30°C. Ideal chlorophyll-a concentrations are relatively low, typically between 0 and 0.3mg/ m^3. The optimal ranges for sea surface height (SSH), salinity, and current velocity are 0.63–0.64m, 33–33.5ppt, and 0.1–0.3m/ s, respectively. Among these, SSH was identified as the most influential factor affecting the distribution of longtail tuna. Habitat Suitability Index (HSI) maps reveal that the distribution of longtail tuna shifts northward toward the end of the La Niña phase, concentrated around coordinates 3–5° S and 114–118° E.

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