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Research Article

Satellite-derived Sea Level Height Trend and Variation associated with Eastern Little Tuna (*Euthynnus affinis*) catch rates in the Makassar Strait

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ABSTRACT

Sea level is a key oceanographic variable that exhibits both spatial and temporal variability and serves as an important indicator of global and regional ocean–climate variability, which can influence fishery productivity. Using satellite observation data, this study aimed to identify patterns and fluctuations in sea level trends and variability, and to examine their effects on the catch rates of Eastern Little Tuna (Euthynnus affinis) in the Makassar Strait over a ten-year period (2013–2022). Sea level time series were generated through averaging calculations and spatial mean mapping to characterize sea level distribution. Histogram analysis was applied to determine the frequency of catch per unit effort (CPUE) across different sea level ranges. The results showed that mean sea level in the Makassar Strait during the study period ranged from 0.48 to 0.78 m. Clear annual and seasonal sea level variability was observed, with higher values (0.65–0.70 m) during the northwest monsoon and lower values (0.50–0.60 m) during the southeast monsoon. Over the ten-year period, sea level increased by approximately 0.13 m. The highest CPUE of Eastern Little Tuna was associated with sea levels between 0.60 and 0.65 m. Histogram analysis further indicated that this sea level range corresponded to the maximum CPUE values. In contrast, higher sea levels ranging from 0.75 to 0.80 m were associated with the lowest CPUE, value of 30 kg/trip.

Keywords: *Euthynnus affinis; Makassar Strait; Sea level; Tren; Variation.*

Introduction

The Makassar Strait is connected to the Pacific Ocean in the north and to the Java Sea and the Flores Sea in the south. As a result, the hydrodynamic conditions of the Makassar Strait are strongly influenced by Pacific Ocean waters, particularly those originating from the western equatorial Pacific. The Makassar Strait is also recognized as a major pathway of the Indonesian Throughflow (ITF), which transports large volumes of warm water from the Pacific Ocean to the Indian Ocean [1]. Owing to its complex oceanographic characteristics and its crucial role in global thermohaline circulation, the ITF region in Indonesia has been extensively studied, including in previous investigations [2], [3].

The Eastern Little Tuna (*Euthynnus affinis*) is a dominant catch in the Makassar Strait and represents a commercially valuable neritic tuna species. Eastern Little Tuna contributes substantially to national fisheries production, with a reported catch value of approximately USD 716,000 in 2020 [4]. According to data from the Indonesian Central Bureau of Statistics, total Eastern Little Tuna landings from the Makassar Strait reached 40,352 tons by 2020. Previous research [5], reported that the exploitation rate (E) of Eastern Little Tuna in the Makassar Strait was 0.64, indicating a high level of fishing pressure and a declining capture potential. As a pelagic species, the distribution and abundance of Eastern Little Tuna are strongly influenced by oceanographic variables, particularly sea surface height (SSH). SSH plays an important role in identifying potential fishing grounds. Several studies [6], [7], have shown that the relationship between SSH and catch per unit effort (CPUE) is associated with the presence of a warm mixed layer above the thermocline, which enhances habitat suitability and prey availability for pelagic fish species.

The current rate of global warming has a significant influence on sea level rise. According to recent estimates [8], the mean annual rate of global sea level rise is approximately 3.1 mm, representing an increase of about 50% compared with the preceding two decades. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report [9], reported that global mean sea level increased by 15–25 cm between 1901 and 2018 as a consequence of climate change. In addition, in 2022, global mean sea level reached a new record high, rising by approximately 101.2 mm (0.101 m) above 1993 levels. The rate of sea level rise is accelerating and is projected to continue increasing in the coming decades. A recent study [10], further indicated that across Indonesian waters, the average rate of sea level rise is approximately 5.84 mm per year, which is nearly twice the current global average.

Sea level represents the vertical distance between the ocean surface and the Earth's reference ellipsoid [11]. Sea level varies dynamically due to multiple processes, including tidal forcing [12], storm-induced waves, upwelling and downwelling [11], as well as long-term influences such as global warming, which contributes to polar ice melt [13]. Variations in sea level can be used to infer key oceanographic features, including ocean circulation patterns and frontal systems [14]. In particular, major ocean dynamic processes such as mesoscale eddies [15], convergence zones, and upwelling can be effectively identified through sea surface height (SSH) observations.

As noted in [16], beyond its physical role, sea level serves as an important global and regional indicator of climate change. Projected future climate change is expected to exert substantial impacts on marine environments by altering key physical characteristics, including sea level [17]. Such changes influence horizontal sea level variability, which is closely associated with shifts in the thermocline and is often linked to the identification of preferred fish habitats [18]. Previous studies have also demonstrated that sea level variability affects the occurrence and distribution of marine species, such as whale sharks [19]. Accordingly, sea level observations are frequently used to describe ocean topographic dynamics [20]. Furthermore, sea level variability has been shown to reflect both local and large-scale climatic events [21].

The ability of synoptic remote sensing techniques to provide broad spatial coverage, high spatial resolution, and multi-year time series through routine and repeated observations has greatly facilitated the application of satellite remote sensing in the marine sector, particularly for oceanographic parameter studies [22]. Spatial analysis enables more precise characterization of sea level variability and is commonly conducted using a Geographic Information System (GIS) [23]. Previous investigations of sea level variability in Indonesian waters have been reported by [24], [25]. In this study, satellite-derived sea level data were used to examine decadal changes from 2013 to 2022, thereby improving understanding of dominant spatial sea level patterns in a key pathway of the Indonesian Throughflow, namely the Makassar Strait. In addition, this study aimed to identify patterns and temporal fluctuations in sea level trends and to assess their potential influence on the catch rates of Eastern Little Tuna in the Makassar Strait.

Materials and Methods

This research was carried out in the Makassar Strait, specifically at coordinates 1°N–5°S and 115–121°E (Figure 1). The Makassar Strait was chosen as the primary research area due to its dynamic and distinctive oceanographic features.

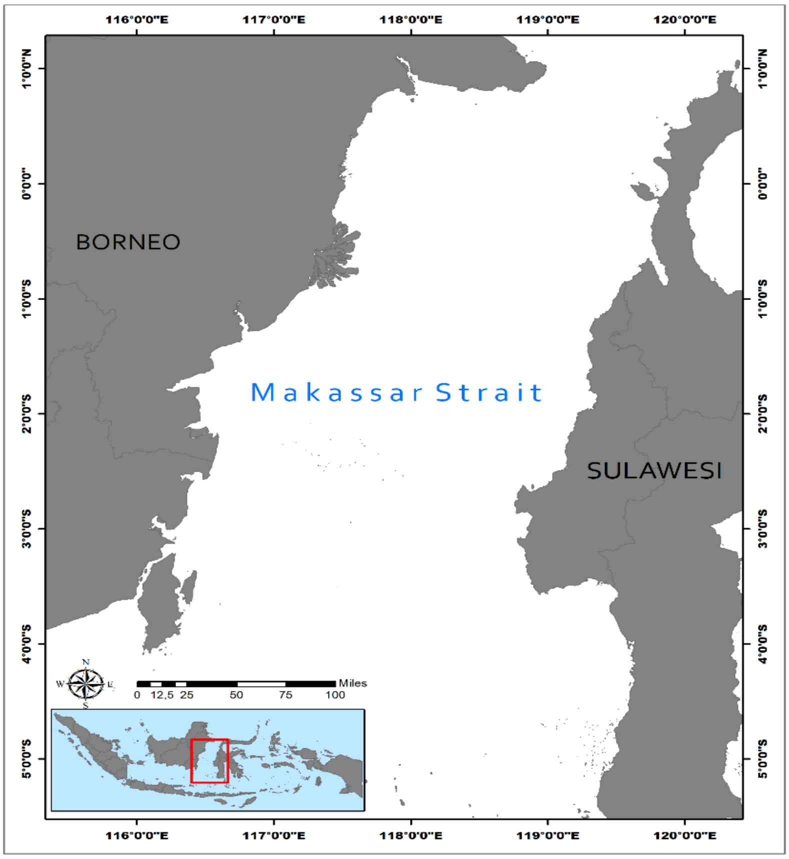

Figure 1. A map illustrating the Makassar Strait as the study area. The inset box on the map delineates the study area within the Indonesian Seas.

The Makassar Strait, which separates the islands of Kalimantan and Sulawesi and serves as a major gateway of the Indonesian Throughflow (ITF), reaches depths of approximately 1,500 m [26]. It is estimated that about 80% of the southward ITF transport from the Pacific Ocean to the Indian Ocean passes through this strait. However, the narrow geometry of the strait constrains the deeper layers of the ITF, as much of its southern section is shallower than 50 m [27]. The data processing period covered ten years, from 2013 to 2022. Monthly sea level data with a spatial resolution of 9 km were analyzed. Fishery data comprised total catch weight (kg), fishing locations (latitude and longitude), catch quantity, and the number of fishing days, as summarized in Table 1.

Satellite-derived sea level data in NetCDF (.nc) format were converted to Microsoft Excel (.xlsx) format using the "Make NetCDF Table View" tool in ArcGIS software. Subsequently, monthly mean sea level values were calculated to generate a continuous time series spanning ten years. Time series analysis was then applied to identify sea level variability and anomalies as a function of time.

Table 1. Oceanographic data specification (Oceanographic Param)

Parameter	Sensor	Unit	Resolution		Sources
			Temporal	Spatial	
Sea level height	CMES	meter	Monthly	9 km	www.marine.copernicus.eu
Fish catches	-	kg	Monthly	-	Ministry of Marine Affairs and Fisheries Republic of Indonesia

Sea level raster data were averaged on a monthly basis for the period 2013–2022 using the "Cell Statistics" function in the Spatial Analyst tools of ArcGIS. Spatial analysis was performed by visualizing the distribution of mean sea level to assess spatial variability. Furthermore, sea level data were overlaid with catch per unit effort (CPUE) data to examine the spatial distribution of Eastern Little Tuna in relation to sea level patterns.

The catch per unit effort (CPUE) approach was employed to assess changes in fishery production. Fishery production data were analyzed using Microsoft Excel and presented as bar charts. Subsequently, fishing locations were integrated with sea surface height (SSH) visualization maps to examine spatial relationships. CPUE values were calculated using the formula proposed by Gulland [28]. (Eq. 1). In addition, histogram analysis was conducted to determine the frequency distribution of Eastern Little Tuna catches across different sea level classes.

$$CPUE = \frac{Catch}{Effort} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

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

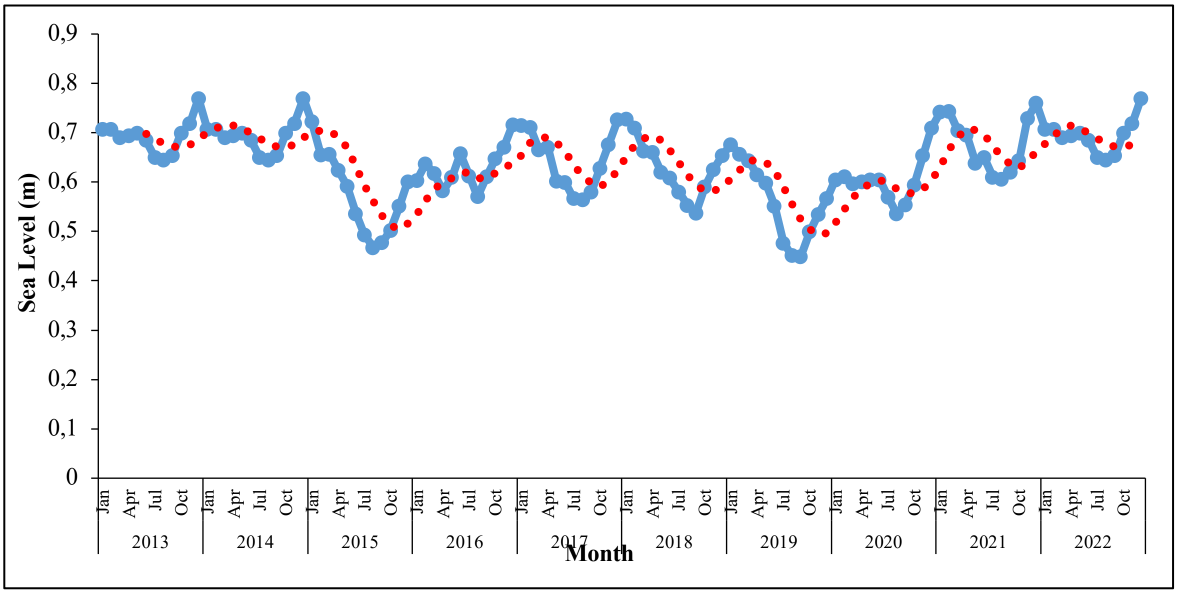

Figure 2. Time series plots of monthly mean sea level in the Makassar Strait for the 2013–2022 period. The dashed red line represents the trendline. This data is sourced from CMES Marine Copernicus. The x-axis represents the month and year, and the y-axis shows the sea level (in meter).

Results and Discussion

Temporal Variation of Sea Level Height

To identify sea level variability, a ten-year time series of mean sea level was plotted (Figure 2). Based on this time series, the temporal dynamics and variability of sea level in the *Makassar Strait* can be examined. The y-axis represents sea level values (m), while the x-axis represents the corresponding month and year.

Sea level in the Makassar Strait ranged from 0.45 to 0.78 m during the study period. The highest mean sea level was recorded in December 2019, whereas the lowest mean value occurred in September 2019. Overall, sea level exhibited pronounced variability from 2013 to 2022 and followed a clear seasonal pattern. Sea level generally decreased during July–August, corresponding to the southeast monsoon, and increased during January and December, associated with the northwest monsoon. The highest sea level (0.78 m) was observed during December 2014 and December 2022 (northwest monsoon), while the lowest value (0.45 m) occurred in August 2019 (southeast monsoon). Sea level also tended to decline toward the second transition season. However, sea level variability across Indonesian waters differs spatially, depending on dominant driving factors. Previous studies have shown that multiple processes contribute to sea level variability in Indonesian seas [28]. In particular, tidal forcing, wind stress, and the movement of water masses from the Pacific Ocean play major roles in modulating sea level [29]. To further elucidate the seasonal characteristics of mean sea level, monthly mean climatology was computed over the ten-year period from 2013 to 2022 (Figure 3).

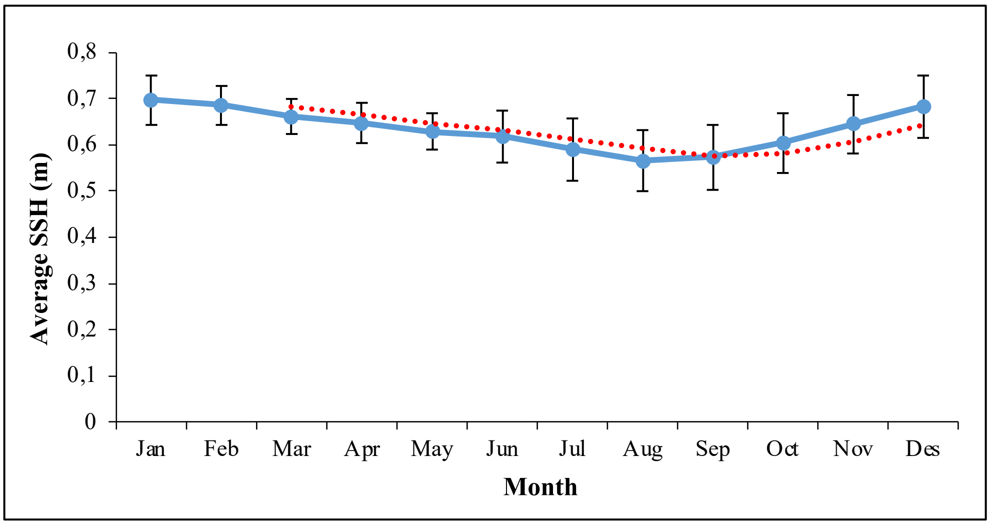

Figure 3. Time series plots of the monthly mean climatology of SSH (in m) during 2013-2022. The dotted red line represents the trend line, while the black vertical bars indicate the standard deviation.

Monthly mean sea level time series clearly illustrate year-round variability in the Makassar Strait. During the second transition season (September–November), sea level generally increased to approximately 0.68–0.69 m. Thereafter, sea level began to decline around March, a trend that persisted through the southeast monsoon and reached a minimum in August, when the mean sea level dropped to about 0.56 m. This seasonal pattern is consistent with previous findings [27], which reported higher sea levels during the Australia–Indonesia monsoon (December–March) and lower sea levels during the southeast monsoon (June–September). A comparison between 2013 and 2022 indicates a notable overall increase in sea level. Based on the mean monthly climatology of sea surface height (SSH), the net sea level rise over the study period was approximately 0.13 m. This upward trend suggests that the Makassar Strait has experienced a general increase in sea level, in agreement with global sea level rise patterns reported in recent assessments [9].

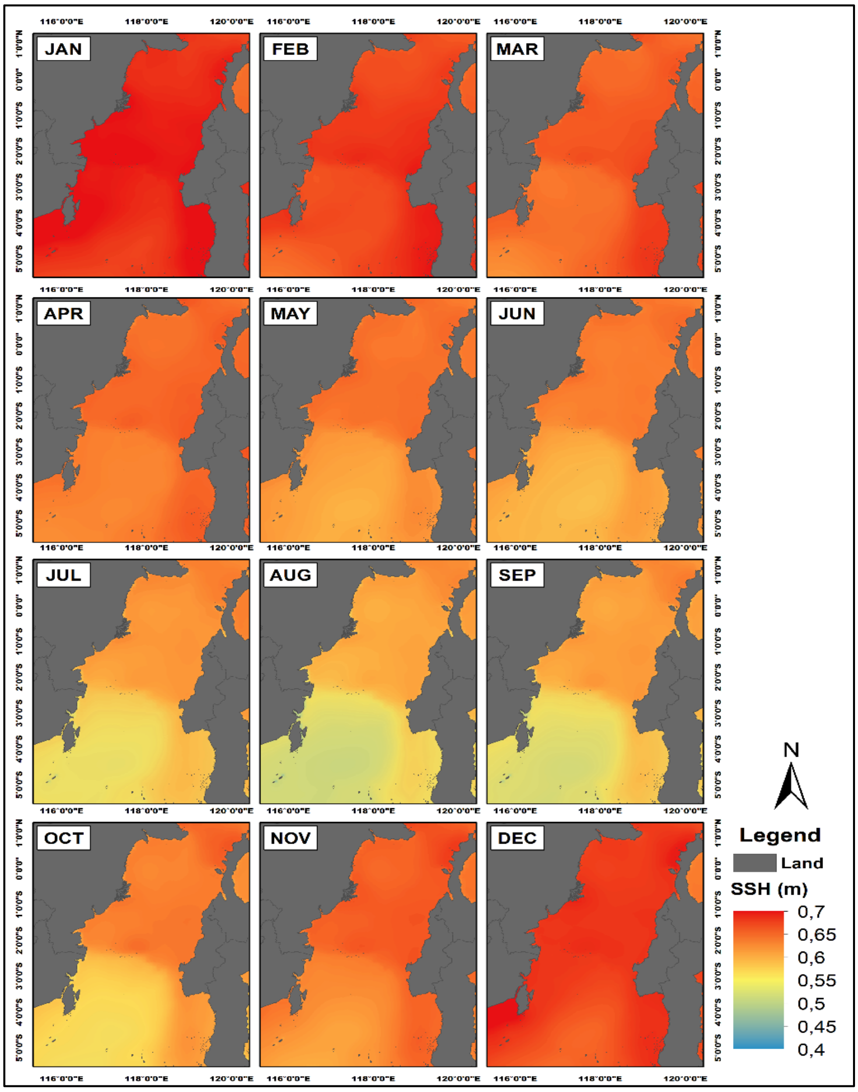

Figure 4. Spatial distribution of the monthly mean climatology of sea level (in m) in the Makassar Strait in 2013–2022.

Spatial Distribution of Sea Level Variation

To better elucidate spatial patterns of sea level variability, the following results present the spatial distribution of mean monthly climatology of sea surface height (SSH) in the *Makassar Strait* during the period 2013–2022 (Figure 4). Color-coded scales ranging from 0.4 to 0.7 m (blue to red), with intervals of 0.05 m, represent variations in sea level. The spatial maps illustrate distinct color gradients that reflect monthly and seasonal differences in sea level across the Makassar Strait over the study period. During December–February (northwest monsoon), the SSH maps are dominated by red hues, indicating elevated sea levels of approximately 0.7 m. This pattern is consistent with previous findings [30], which reported increased sea levels in the Makassar Strait during December. In March, SSH values began to decline but remained relatively high, ranging from 0.6 to 0.65 m. This decreasing trend continued through June, marking the onset of the southeast monsoon. From July to September, sea level reached its lowest values, with pronounced spatial gradients observed particularly in the southern

Makassar Strait between 3–5°S and 116–118°E, where SSH ranged from 0.5 to 0.6 m. In November, corresponding to the end of the second transition season, sea level increased again to approximately 0.6–0.65 m. The southern portion of the Makassar Strait exhibits a stronger monsoonal influence on SSH, which progressively weakens toward the northern region [31].

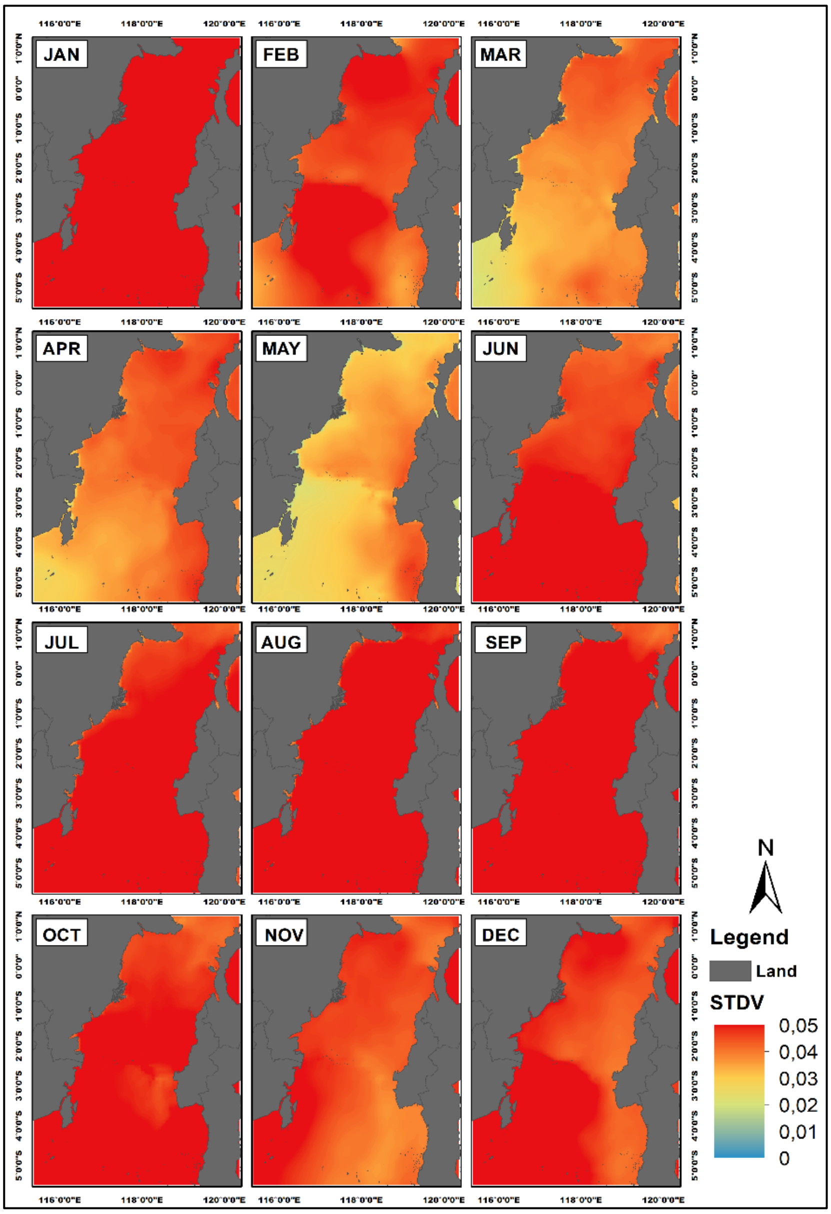

Figure 5. Standard Deviation of the monthly mean of Sea Level in the Makassar Strait 2013-2022.

The sea level gradient across the Makassar Strait is primarily driven by pressure differences between water masses originating from the Pacific Ocean and the Indian Ocean. From the onset of the southeast monsoon to the beginning of the second transitional season (around September), this sea level gradient reaches its maximum. Regional sea level variability can differ substantially from global sea surface temperature (SST) patterns due to the combined influence of bathymetry and dynamic factors such as tides, storm activity, and large-scale climate modes including El Niño [32]. Topographic features strongly control sea level distribution within narrow coastal straits, effectively isolating them from sea level signals observed outside the strait [27]. Seasonal sea level differences and monsoonal wind variability are closely correlated and jointly dominate the seasonal fluctuations of the upper-layer Indonesian Throughflow (ITF) in the southwestern Pacific region [33], [34]. The ITF transports large volumes of relatively warm and low-salinity water from the western tropical Pacific to the cooler southern tropical Indian Ocean via the Makassar Strait. Consequently, strong correlations have been observed between sea surface height (SSH) variability and ITF transport at both the entrance and exit regions of the ITF pathway [35].

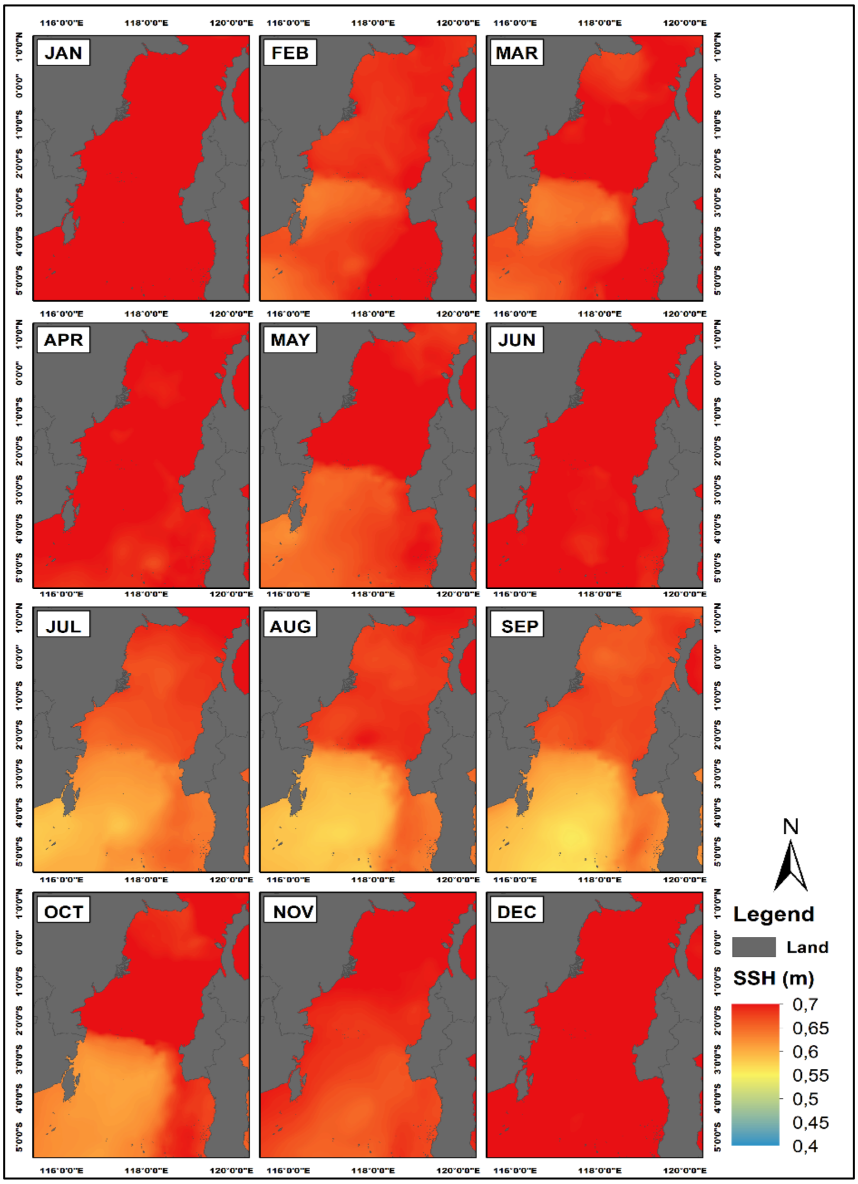

Figure 6. A map of average sea level variation in the Makassar Strait in 2022.

The distribution map of standard deviation illustrates the months characterized by elevated sea level variability (Figure 5). The standard deviation map indicates that the Makassar Strait experiences relatively high sea level variability throughout the year. During the northwest monsoon, standard deviation values range from 0.04 to 0.05 m, with stronger variability observed in the southern part of the strait. Sea level variability then decreases during the first transitional season (March–May), with standard deviation values between 0.02 and

0.04 m. Variability reaches its maximum during the southeast monsoon and extends into the second transitional season, peaking at approximately 0.05 m, before declining again in November. These patterns highlight the strong influence of strait topography on sea level distribution and variability [27]. o provide a comparison with the long-term climatology (2013–2022), Figure 6 presents the mean monthly sea level for 2022, representing more recent conditions.

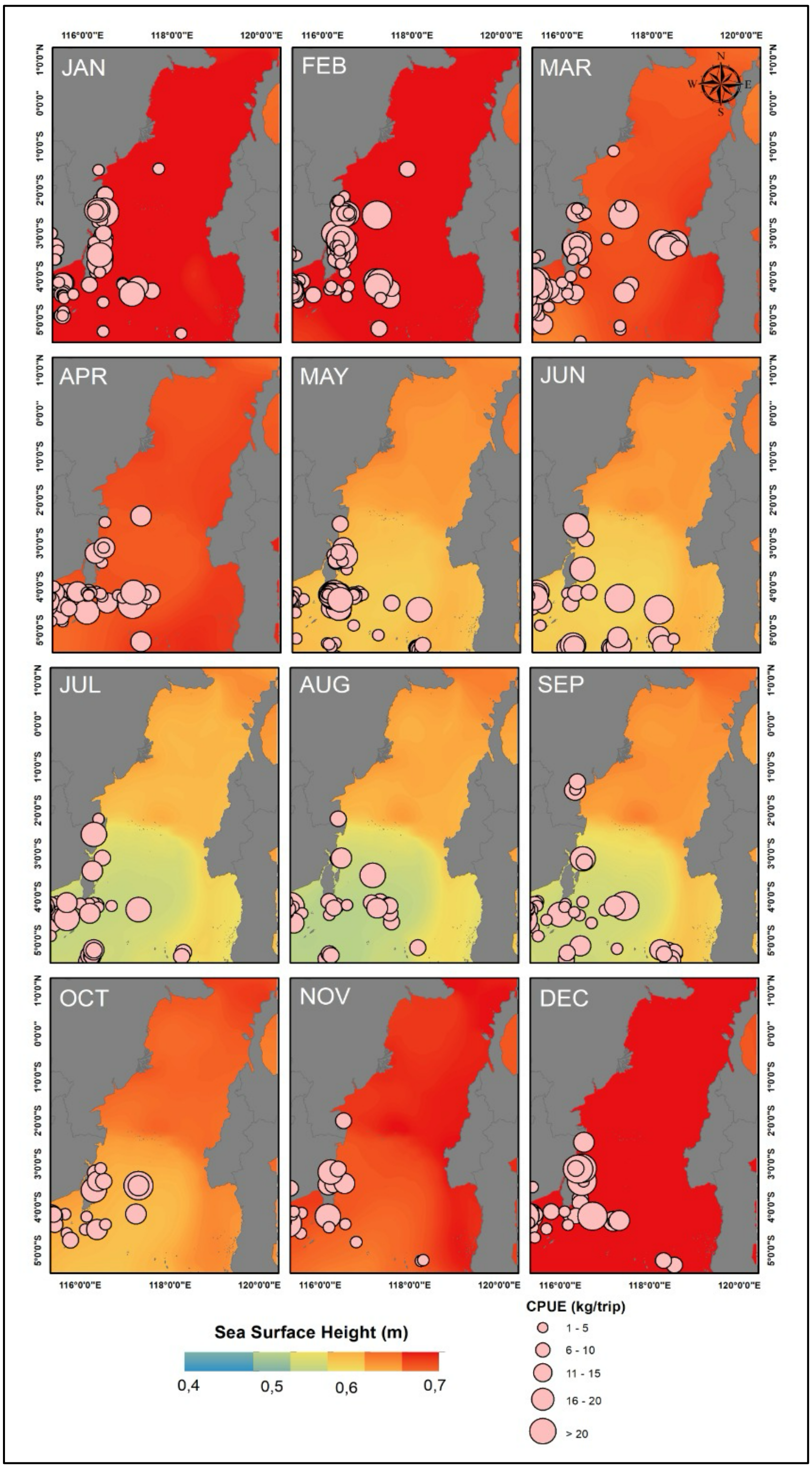

Figure 7. The spatial map displays an overlay of mean sea level and Eastern Little Tuna catches in the Makassar Strait from January to December 2017. Color bars represent sea level heights, and pink dots denote the precise fishing location along with the Catch Per Unit Effort (CPUE) for Eastern Little Tuna.

In 2022, sea level in the Makassar Strait remained relatively high throughout the year, ranging from approximately 0.5 to 0.7 m. The maximum sea level (~0.7 m) was observed in January and December 2022. In February and March, slightly lower sea levels (~0.65 m) were evident in the southern and central parts of the strait, while higher mean sea levels persisted in the northern region. Sea level decreased during the southeast monsoon (July–August) and the second transitional season (September), when lower values (0.5–0.6 m) were concentrated in the southernmost Makassar Strait, coinciding with the shift from the first transitional season to the southeast monsoon. During this period, the northern region remained dominated by relatively higher sea levels (~0.65 m). Sea level increased again in November, corresponding to the end of the second transitional season. Overall, sea level in 2022 was consistently higher than the ten-year monthly mean climatology (2013–2022), indicating a positive anomaly relative to the long-term average. This elevated sea level may be partly associated with regional climate variability linked to the El Niño–Southern Oscillation (ENSO) [13]. According to the National Oceanic and Atmospheric Administration (NOAA), La Niña conditions persisted throughout 2022. During La Niña phases, the Indonesian Throughflow (ITF) transports relatively warmer water, which contributes to deepening of the thermocline [16]. This process plays an important role in modulating ocean–atmosphere interactions, thereby influencing regional weather patterns and marine ecosystem dynamics.

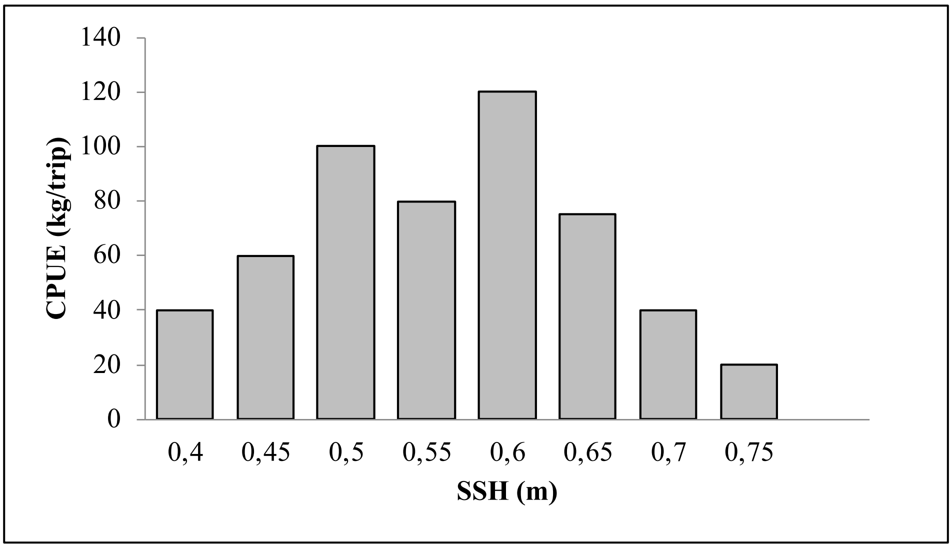

Figure 8. Histogram analysis of sea level and average CPUE of Eastern Little Tuna.

Spatial Distribution of Sea Level and Eastern Little Tuna

The following results describe the spatial overlay of monthly and seasonal sea level variability with fishing locations in 2017 in the *Makassar Strait* (Figure 7). Sea level reached its peak during the northwest monsoon (December–February), coinciding with relatively high catch per unit effort (CPUE) values ranging from 7.6 to 25 kg trip^{-1}. During this period, fishing activities were predominantly concentrated in the central to western parts of the Makassar Strait.

During the first transitional season, CPUE values ranged from 13.4 to 38 kg trip^{-1}. During this period, sea level remained relatively high (0.60–0.66 m) but showed a gradual decline toward the end of the season, decreasing to approximately 0.56–0.60 m. Subsequently, during the southeast monsoon (June–August) and the second transitional season (September–November), CPUE values decreased concurrently with a reduction in sea level. During the southeast monsoon, sea level ranged from 0.52 to 0.58 m in the southern region and from 0.58 to 0.64 m in the northern region of the Makassar Strait, with corresponding mean CPUE values of 6.3 and 7.2 kg trip^{-1}, respectively. In the second transitional season, CPUE values increased slightly to a range of 10–19 kg trip^{-1}, while sea levels varied from 0.48 to 0.60 m in the southern sector and from 0.64 to 0.68 m in the northern sector of the strait. The observed sea level contrast between the northern and southern regions of the Makassar Strait is attributed to opposing influences of water masses originating from the Pacific Ocean in the north and the Indian Ocean in the south [36]. The Indonesian Throughflow (ITF) plays a substantial role in shaping these patterns, with its influence becoming more pronounced during the eastern (southeast monsoon) season [37]. Overall, the northwest monsoon and the first transitional season are characterized by relatively higher sea levels, which coincide with the highest CPUE values. These conditions strongly influence the spatial distribution of Eastern Little Tuna through sea level driven habitat variability.

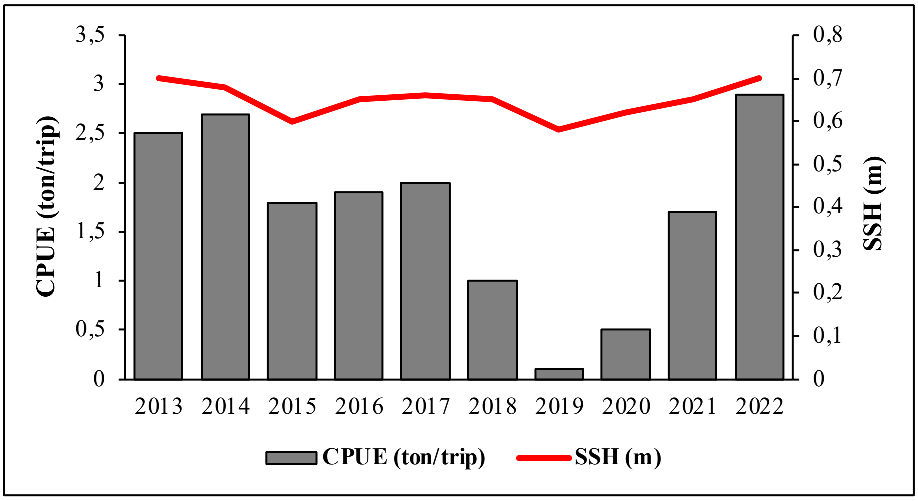

Figure 9. Annual variation of CPUE of Eastern Little Tuna (grey bar) and sea level (red line) in 2013–2022 in the Makassar Strait.

The El Niño Southern Oscillation (ENSO) exerts a strong influence on this region by modifying surface wind patterns and ocean circulation, and by inducing variability in sea surface temperature (SST) and salinity, as well as shifts in thermocline depth driven by wind forcing. These physical changes can subsequently alter sea surface height (SSH) [38]. Variations in the intensity of ENSO events can therefore affect interconnected marine ecosystems, leading to changes in the spatial and temporal distribution and abundance of tuna resources [39]. In addition, prey availability plays a key role in shaping tuna migratory behavior, as tuna tend to track favorable habitats that are often associated with sea level and thermocline variability [40]. Numerous studies have provided strong evidence that ENSO events significantly influence tuna distribution and abundance across different oceanic regions [41], [42].

To identify the sea level range associated with optimal fish yield, histogram analysis was conducted by extracting sea level values at fishing locations within the Makassar Strait. In the resulting histogram, the x-axis represents sea level values ranging from 0.4 to 0.8 m at 0.1 m intervals, while the y-axis represents catch per unit effort (CPUE), ranging from 30 to 120 kg trip^{-1} (Figure 8).

The histogram indicates that sea levels between 0.60 and 0.65 m are associated with the highest catch per unit effort (CPUE), reaching up to 120 kg trip^{-1}. In contrast, the lowest CPUE values (approximately 30 kg trip^{-1}) were observed at higher sea levels ranging from 0.75 to 0.80 m. The optimal sea level range identified in this analysis is consistent with the maximum catch recorded in 2022, which reached 2.88 tons trip^{-1} at an average sea level of approximately 0.68 m. Other notably high CPUE values, ranging from 2.00 to 2.29 tons trip^{-1}, were recorded in 2013, 2014, and 2017, corresponding to sea levels between 0.60 and 0.70 m (Figure 9).

The lowest CPUE values were recorded in 2019, coinciding with the lowest observed sea level conditions. In contrast, CPUE tended to increase during La Niña phases, which are associated with elevated sea surface height (SSH). This pattern is illustrated in the graph above, where the average CPUE of Eastern Little Tuna peaked in 2022, corresponding to a prolonged La Niña event. Previous research Syamsuddin *et al.* [43], has similarly reported that Eastern Little Tuna catches increase during La Niña periods, following SSH enhancement linked to rising sea surface temperature (SST).

Conclusion

The Makassar Strait has experienced significant sea level trends and variations from 2013 to 2022, which revealed an annual and seasonal pattern with the highest values (0.65–0.7 m) during the northwest monsoon and the lowest during the southeast monsoon (0.5–0.6 m). Over this decade, sea levels have increased by approximately 0.13 m. The optimal sea level range for catching Eastern Little Tuna (*Euthynnus affinis*), with a catch per unit effort (CPUE) of 120 kg/trip, is between 0.6 and 0.65 m, aligning with the peak catch in 2022. However, the study does not account for regional climate impacts like the El Niño Southern Oscillation (ENSO) on sea levels in the Makassar Strait, indicating a need for further research to explore the relationship between sea level fluctuations and ENSO in this area.

Acknowledgment

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Conflict of interest

Authors declare no conflict of interest regarding the study.

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