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Analysis of Synergistic Oceanographic Factors Influencing Seasonal Whale Shark (*Rhincodon typus*) Appearance in Botubarani Waters, Gorontalo Bay, Indonesia

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ABSTRACT

This study aimed to analyze the influence of marine environmental parameters on the occurrence of whale sharks and to identify seasonal differences in their appearances. Data were collected monthly from June 2023 to May 2024, covering sea surface temperature (SST), current speed, chlorophyll-a concentration, and the number of whale shark sightings. SST and chlorophyll-a data were obtained from MODIS-Aqua satellite imagery, while current speed was modeled using the FM Flow Model module in MIKE 21 software. The analysis was conducted seasonally (Eastern monsoon, transitional season II, western monsoon, and transitional season I) over the same one-year period. Statistical methods included Pearson correlation, multiple linear regression, one-way ANOVA, and Tukey's HSD post-hoc test. The results indicated that chlorophyll-a concentration had a significant positive correlation (r= 0.63; P< 0.05) with whale shark sightings, while current speed exhibited a significant negative correlation (r = -0.63; P< 0.05). The multiple regression model accounted for 59.5% of the variation in sightings (R^2 = 0.595). Tukey's HSD post-hoc analysis revealed a significant difference only between the eastern monsoon and transitional season II (P = 0.025), with the eastern monsoon representing the peak occurrence period. During this time, sightings increased by an average of 1.37 individuals per day compared to transitional season II. This peak occurred under optimal SST conditions ranging from 27.5 to 28°C, chlorophyll-a concentrations between 0.58 and 1.83mg/ m³, and relatively low current speeds of 0.11 to 0.13m/ s. These findings provide a scientific basis for managing whale shark conservation and protection areas in Botubarani Waters, Gorontalo Bay, and support an adaptive approach to whale shark tourism management.

INTRODUCTION

Whale sharks (*Rhincodon typus*) are the largest living fish species and are distributed throughout tropical and warm waters worldwide **(Guzman *et al.*, 2022a)**. Despite this wide distribution, most studies focus on specific aggregation sites, whereas whale shark behavioral ecology and demographics can vary significantly by location **(Hardenstine *et al.*, 2022)**. Whale sharks are filter feeders and highly migratory. Since the early 1990s, ecotourism centered on whale sharks has increased significantly. When managed responsibly, such tourism can strengthen local economies, support marine conservation, and raise public awareness about the importance of marine biodiversity—without disrupting whale sharks' feeding or natural behavior **(Reinero *et al.*, 2024)**. However, this tourism potential can also pose risks to whale sharks **(Maruanaya *et al.*, 2022)**.

Understanding the seasonal emergence patterns of whale sharks is crucial for supporting sustainable conservation and tourism practices. Marine organisms depend heavily on environmental conditions, both in surface waters and along the seafloor. Oceanographic factors such as sea surface temperature (SST), chlorophyll-a concentration, and current speed play key roles in shaping whale shark distribution and movement **(Copping *et al.*, 2018; Guzman *et al.*, 2022)**. These variables affect food availability, particularly zooplankton and small fish such as *teri* fish (*Stolephorus* spp.) **(Macena & Hazin, 2016; Boldrocchi *et al.*, 2020; Yasir *et al.*, 2024)**.

Seasonal emergence patterns have been observed globally. For example, whale sharks appear at Ningaloo Reef (Australia) and Tofo Beach (Mozambique) during autumn and colder months, coinciding with increased productivity after coral spawning **(Norman *et al.*, 2017)**. Similarly, on Mexico's Yucatán Peninsula, whale sharks gather to feed on plankton and fish larvae. Migration behavior is also linked to oceanographic variables, particularly current speed **(Guzman *et al.*, 2022)**. These patterns are consistent across regions, where whale sharks aggregate in areas with enhanced food availability **(D'Antonio *et al.*, 2024)**. This highlights the role of seasonal oceanographic dynamics in shaping whale shark behavior, especially their foraging and movement patterns. Whale sharks tend to remain in plankton-rich zones during productive seasons and disperse during less productive periods.

Although several studies have examined whale shark aggregations globally—including in Mexico, the Philippines, and Mozambique—similar research in Indonesia remains limited, particularly in the Gorontalo Bay Marine Protected Area. Most Indonesian studies have focused on population characteristics, tourism behavior, and legal protection, while quantitative analyses of how oceanographic dynamics influence whale shark emergence remain scarce. This lack of data limits effective habitat management and ecotourism planning.

In Indonesia—specifically in Botubarani waters, part of Gorontalo Bay Marine Protected Area—whale sharks have been observed periodically since 2016. This area is considered a potential conservation and tourism site, with whale sharks serving as a major attraction. Due to its proximity to the coastline, Botubarani is well-suited for educational tourism based on direct observation **(Himawan *et al.*, 2022; Green *et al.*, 2023)**. However, no studies have quantitatively examined how SST, chlorophyll-a, and current speed affect seasonal whale shark occurrence in this region. At the same time, tourism managers require reliable seasonal data to guide sustainable practices and protection efforts.

According to **Rowat *et al.* (2007)**, whale sharks are often found in shallow, coastal waters with average depths of around 7 meters. In Botubarani, they are commonly seen within 100 meters of the coast **(Yusma *et al.*, 2024)**. These docile animals interact easily with humans, making them ideal for tourism development **(Himawan *et al.*, 2022; Green *et al.*, 2023)**. However, such interactions must be carefully managed to ensure that tourism does not disturb the species, and that conservation remains the priority **(Legaspi *et al.*, 2020)**.

Whale shark data collected by BPSPL Makassar from 2016 to 2024 identified 59 individual male whale sharks in Botubarani waters, with peak appearances in May, June, and July **(Yusma *et al.*, 2024)**. This seasonal pattern aligns with global findings. For instance, satellite tagging at Ningaloo Reef and other sites shows that female whale sharks tend to inhabit deeper, cooler offshore waters, while males are more likely to aggregate in warmer, nearshore areas **(Bignell *et al.*, 2025)**. Long-term datasets on whale shark daily presence in Botubarani remain underdeveloped, and incorporating them could reveal ecological patterns linked to oceanographic conditions. Such data would support seasonal conservation policy development in the region.

In this context, the primary hypothesis of this study posits that seasons marked by increased marine productivity coincide with higher frequencies of whale shark sightings. Seasonal variation suggests that whale shark appearances are not random but instead follow specific temporal patterns influenced by ocean productivity. We hypothesize that high chlorophyll-a concentrations and low current speeds promote plankton proliferation, thus attracting whale sharks.

Additionally, it is suspected that whale shark occurrence differs significantly across oceanographic seasons—namely, the western monsoon, transitional season I, eastern monsoon, and transitional season II. Identifying these differences is critical to understanding the species’ ecological cycles.

By identifying seasonal patterns, this study aimed to provide a scientific foundation for sustainable ecotourism. Tourism timing can be adjusted to align with peak whale shark activity while minimizing ecological disruption. This strategy promotes responsible tourism that enhances both visitor experience and species conservation.

Moreover, the study's findings are expected to inform science-based conservation strategies, emphasizing seasonal oceanographic dynamics as a component of adaptive management for the Gorontalo Bay conservation area.

Therefore, the objective of this research is to analyze how oceanographic parameters (SST, chlorophyll-a, and current speed) influence the seasonal occurrence of whale sharks in Botubarani Waters. This information can guide optimal tourism timing and conservation initiatives. The study integrates both primary and secondary data, covering a full annual cycle (June 2023 to May 2024) and historical data from 2016 to 2023 to provide a comprehensive understanding.

This research directly supports several Sustainable Development Goals (SDGs), including SDG 14 (Life Below Water) by contributing data for marine conservation, SDG 12 (Responsible Consumption and Production) by promoting sustainable tourism, and SDG 15 (Life on Land) by helping protect endangered species from extinction.

MATERIALS AND METHODS

1. Study area

The research was conducted is in the waters of Botubarani, which is part of Gorontalo Bay Marine Protected Area, Gorontalo Province, Indonesia (Fig. 1).

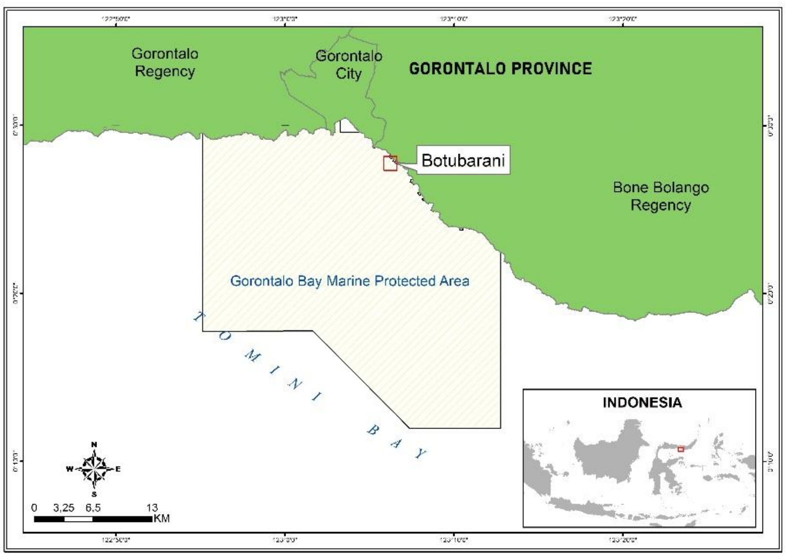

Fig. 1. Map of study locations

2. Time and data sources

Data were collected over an annual cycle, from June 2023 to May 2024, covering the eastern season, western transition season II, western season, and transition season I.

a) **Primary data** are the daily frequency of whale shark appearances recorded directly by field observers in collaboration with the Basic Tourism Group and BPSPL Makassar.

b) **Secondary data** consist of:

- Sea surface temperature (SST, °C) and chlorophyll-a concentration (mg/m³) from MODIS-Aqua satellite imagery,
- Surface flow speed (m/s) from hydrodynamic modeling results using the Flow Model (FM) module in MIKE 21 software,

- Historical data on the emergence of whale sharks (2016–2023) from the Makassar Coastal and Marine Resources Management Center (BPSPL) database and community observations.

3. Data Aaalysis

a) The Pearson correlation test was used to identify the relationship between each oceanographic parameter and the frequency of whale shark appearances.
b) Multiple linear regression was used to analyze the simultaneous contribution of SST, chlorophyll-a, and current to the occurrence of whale sharks.
c) One-way variant analysis (One-Way ANOVA) and Tukey HSD follow-up tests were conducted to determine significant differences in the occurrence of whale sharks between seasons.
d) The data were visualized as a box plot to support statistical interpretation.

RESULTS

1. Distribution of oceanographic parameters

1.1. Sea surface temperature distribution (SST)

The distribution of sea surface temperature (SST) in the Gorontalo Bay conservation area shows spatial-temporal variations that harmonize with the annual seasonal pattern (Fig. 2).

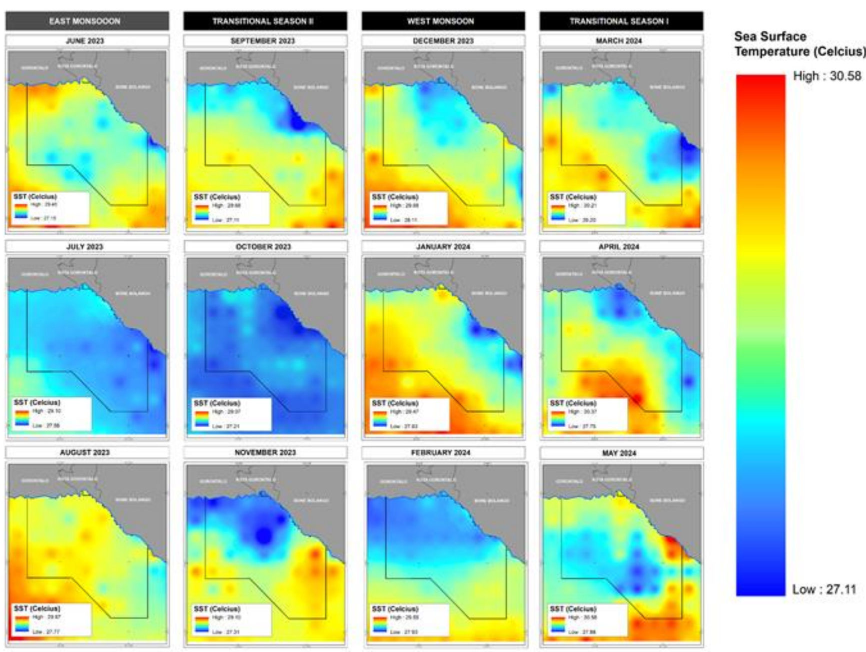

Fig. 2. Sea surface temperature distribution (SST) map of the Gorontalo Bay water conservation area in the eastern season, transition II, western season, transition season I

In the eastern season (June–August 2023), the highest temperature was recorded at 28°C in July, while the lowest temperature reached 27.5°C in the offshore area. This season is characterized by a significant drop in temperature, particularly in July, which suggests upwelling activity in the central and southern waters of Tomini Bay. During the transition season II (September–November 2023), the temperature range varies from 28.5 to 29°C, with a more even distribution of low temperatures, especially in September, indicating that sea conditions are starting to become dynamic due to the transition in wind patterns.

In the western season (December 2023 – February 2024), sea temperatures tend to be warm and stable, with the highest temperature reaching 29.2°C in February and the lowest at 28.5°C, reflecting a relatively calm water column and minimal vertical mixing. In contrast, the transition season I (March–May 2024) shows fluctuations with a maximum temperature of 30.3°C in May and a minimum temperature of 29.8°C in March. The cooling that began to occur in the central and southern areas in April and May showed early indications of a mild upwelling process. This SST distribution pattern is crucial for predicting the optimal time for the emergence of marine megafauna, such as whale sharks, and serves as a scientific basis for conservation management and season-based sustainable tourism planning.

1.2. Chlorophyll-a distribution

The oceanographic parameters in a body of water have a varied distribution. The distribution of SST and chlorophyll-a is closely related to the appearance of whale sharks in the water. This is because fish have a tolerance for their environment that enables them to survive, grow, and reproduce (Fig. 3).

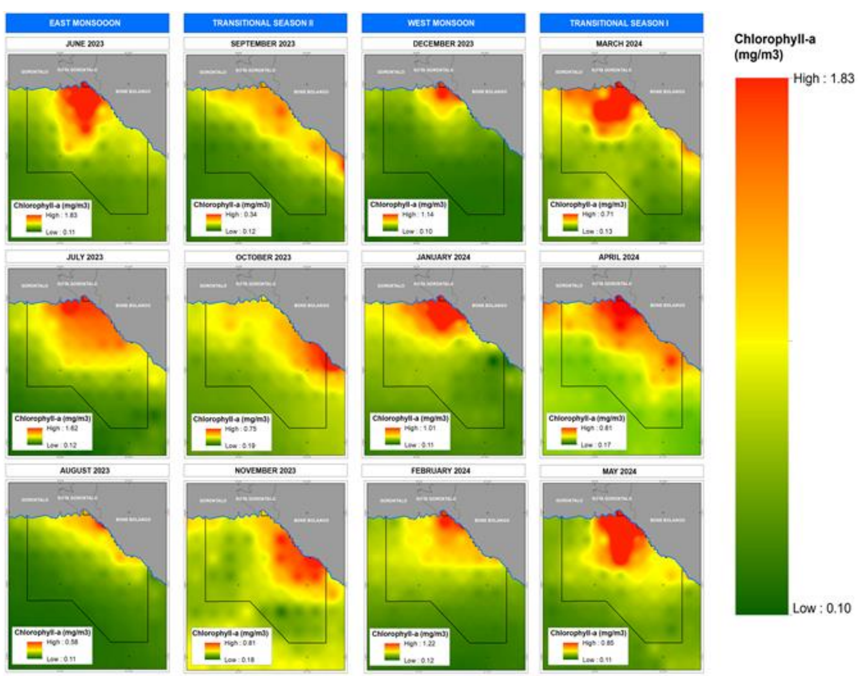

Fig. 3. Chlorophyll-a distribution map of Gorontalo Bay water conservation area in the eastern season, transition II, western season, transition season I

During the eastern season (June–August 2023), chlorophyll-a concentrations in Gorontalo Bay peaked at 1.83 mg/m³ in June, signifying elevated water productivity influenced by easterly winds and potential upcurrent activities in coastal regions. Despite a gradual decline observed in July and August, the relatively elevated concentrations indicate enhanced phytoplankton production, which constitutes a primary food source for marine megafauna, such as whale sharks. As the region transitioned into the second transition season (September–November 2023), chlorophyll-a levels significantly decreased to 0.34mg/ m³ in September, coinciding with a decline in vertical mixing processes and alterations in water circulation patterns, thereby dispersing the productive zones.

During the western season (December 2023 – February 2024), an increase in chlorophyll-a concentrations was observed, with a maximum of 1.22mg/ m³ in February, driven by nutrient runoff from the mainland resulting from high precipitation levels. The increase in chlorophyll-a concentrations continues into the first transition season (March–May 2024) and peaked at 0.85mg/ m³ in May, characterized by dynamic distribution patterns of concentrations in the water of the Gorontalo Bay Conservation Area.

1.3.Current speed

The data presented in Table (1) are validated through direct field measurements conducted over one complete tidal cycle period (30 tidal cycles) from November 1st to November 30th, 2023, in Botubarani waters. Validation results indicated an average measurement error of -4.23%, with the field-measured current speed being higher than the model predictions. Despite this error margin, the measurements are considered sufficiently accurate to ensure the consistency and reliability of the current speed data reported across different seasonal periods.

Table 1. One-year cycle current speed (June 2023 – May 2024), Botubarani Waters

Current speed (m/s)	East Monsoon			Transitional Season II			West Monsoon			Transitional Season I		
	Jun 2023	Jul 2023	Aug 2023	Sep 2023	Oct 2023	Nov 2023	Dec 2023	Jan 2024	Feb 2024	Mar 2024	Apr 2024	May 2024
Max. Current speed (m/s)	0.26	0.25	0.26	0.34	0.42	0.31	0.40	0.37	0.38	0.26	0.29	0.31
Min. Current Speed (m/s)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.05	0.08
Aver. Current speed (m/s)	0.12	0.11	0.13	0.18	0.21	0.14	0.20	0.14	0.22	0.16	0.16	0.17

The current speed for the one-year cycle (June 2023 – May 2024) of the Botubarani waters is shown in Table (1) above. The current speed in the eastern season (June–August 2023) was the lowest compared to other seasons, with the average (June–August) averaging

0.12 m/s. The monthly lowest value recorded in July 2023 was 0.11 m/s, the minimum point during the observation period. This shows the relatively calmer water conditions throughout this season. A significant increase occurred in the transition season II (September–November 2023), with an average current speed of 0.18 m/s. October 2023 recorded the highest speed of the season of 0.21 m/s, which is included in the three highest values in the annual cycle.

Furthermore, during the western season (December 2023–February 2024), the average current speed is 0.18m/ s, with a peak of 0.21m/ s in February 2024. This season features the most intense ocean current dynamics, in line with the western season's more extreme atmospheric and tidal conditions. Data for the transition season I (March–May 2024) showed an average current speed of 0.16m/ s, with a peak of 0.17m/ s in May 2024. Although the intensity is reduced compared to the western season, the current speed remains relatively high, indicating a dynamic change ahead of the upcoming eastern season.

Table 2. Seasonal and monthly summary of oceanographic parameters and whale shark (*Rhincodon typus*) sightings in Botubarani Waters, Gorontalo Bay (June 2023 – May 2024)

Season	Month	SST (°C)	Chlorophyll-a (mg/m³)	Current speed (m/s)	Sightings (Total/Days)	Days Without Sightings	Avg. Sightings (Indiv./Day)
East Monsoon	June 2023	27.5	1.83	0.12	82 / 30	0	2.73
	July 2023	28.0	1.62	0.11	93 / 31	0	3.00
	August 2023	27.8	0.58	0.13	64 / 31	3	2.06
Transitional Season II	September 2023	28.5	0.34	0.18	40 / 30	4	1.33
	October 2023	29.0	0.75	0.21	33 / 31	7	1.06
	November 2023	28.8	0.81	0.14	39 / 30	7	1.30
West Monsoon	December 2023	28.5	1.14	0.20	39 / 31	2	1.26
	January 2024	28.7	1.01	0.14	62 / 31	0	2.00
	February 2024	29.2	1.22	0.21	55 / 29	0	1.90
Transitional Season I	March 2024	29.8	0.71	0.16	35 / 31	5	1.13
	April 2024	30.1	0.61	0.16	71 / 30	3	2.37
	May 2024	30.3	0.85	0.17	60 / 31	7	1.94

2. Statistical analysis

2.1. Pearson correlation analysis

Pearson's correlation analysis was conducted using SPSS to examine the relationship between oceanographic factors and the average number of whale shark occurrences per day. The analysis revealed a significant correlation between the average daily occurrence of whale sharks and two oceanographic parameters (Table 3).

Table 3. Pearson correlation matrix of environmental parameters and whale shark sightings

	Sea Surface Temperature (°C)	**Current speed (m/s)**	**Chlorophyll-a (mg/m³)**	**Average Sightings (Individuals/ Day)**
Sea Surface Temperature (°C)	1	0.488	-0.463	-0.320
Current speed (m/s)	0.488	1	-0.380	-0.630*
Chlorophyll-a (mg/m³)	-0.463	-0.380	1	0.630*
Average Sightings (Individuals/Day)	-0.320	-0.630*	0.630*	1

(*) Significant correlation at $P < 0.05$, confidence interval = (95% CI)

2.2.Multiple linear regression

The coefficients from the multiple linear regression analysis in SPSS illustrate the influence of each independent variable on whale shark occurrence (Table 4). Whale sharks were observed more frequently under conditions of slower ocean currents and higher chlorophyll-a concentrations. In contrast, sea surface temperature (SST) did not show a statistically significant effect on whale shark occurrence patterns. The regression model accounted for 59.5% of the variation in whale shark sightings ($R^2 = 0.595$), indicating a moderate level of explanatory power.

Overall, the model demonstrated a trend approaching statistical significance. The ANOVA test produced an F-value of 3.911, with a corresponding p-value of 0.055, suggesting that the model was marginally non-significant. This result implies that the combination of SST, current speed, and chlorophyll-a collectively contributes to explaining variability in mean whale shark sightings, though the significance level was slightly above the conventional threshold of 0.05.

Table 4. Multiple linear regression coefficients for whale shark sighting

Variable	Unstandardized Coefficients (B)	Std. Error	Standardized Coefficients (Beta)	T	Sig. (*P*-value)
(Constant)	-0.885	5.629		-0.157	0.879
Sea Surface Temperature (°C)	0.123	0.198	0.170	0.617	0.554
Current speed (m/s)	-9.425	4.786	-0.518	-1.969	0.084
Chlorophyll-a (mg/m³)	0.757	0.383	0.512	1.975	0.084

Note: Model Summary: R Square = 0.595, Adjusted R Square = 0.443, F-statistic = 3.911, Sig. F Change = 0.055

Analysis of the model's contribution showed that current speed (β = -0.518) and chlorophyll-a (β = 0.512) were the most significant predictors. These findings align with correlation analysis, suggesting that whale sharks appear more frequently when currents slow down and chlorophyll-a concentrations increase. However, in this combined model, the significance was at the marginal level (*P*= 0.084), indicating a significant influence trend.

2.3. Tukey HSD advanced test

A follow-up Tukey HSD test has been performed to identify specific differences between seasons. Follow-up tests of Tukey HSD showed that the only significant comparison was between the eastern season and transition II (*P* = 0.025), with an average difference in occurrence of 1.37 individuals per day. The appearance of whale sharks differed significantly between the eastern and transitional II seasons. In the eastern season (June–August), average emergence peaks are likely due to relatively lower temperatures, moderate currents, and high feed availability (chlorophyll-a). In contrast, the transition season II (September–November) tends to be characterized by unstable oceanographic conditions and decreased water productivity, which significantly reduces the occurrence of whale sharks. The test results are presented in Table (5) below.

Table 5. Tukey HSD post-hoc test for seasonal differences in whale shark sightings

Season (I)	Season (J)	Mean Diff (I-J)	Std. Error	Sig. (*P*-value)	Significant
East Monsoon	Transitional II	1.36667	0.36828	0.025	Yes
East Monsoon	West Monsoon	0.87667	0.36828	0.159	No

East Monsoon	Transitional I	0.78333	0.36828	0.224	No
Transitional II	East Monsoon	-1.36667	0.36828	0.025	Yes

DISCUSSION

1. Whale shark emergence trends by season

The average monthly distribution of whale shark (*Rhincodon typus*) sightings from June 2023 to May 2024, categorized by tropical seasonal classification, is presented in Fig. (4). The highest frequency of sightings occurred during the eastern monsoon season (June–August), with an average of 2.6 individuals per day. In contrast, sightings declined significantly during the transitional season II and the western monsoon, with averages falling below 1.5 individuals per day. This pattern indicates a pronounced seasonal aggregation trend, aligning with global findings on whale shark aggregation behavior.

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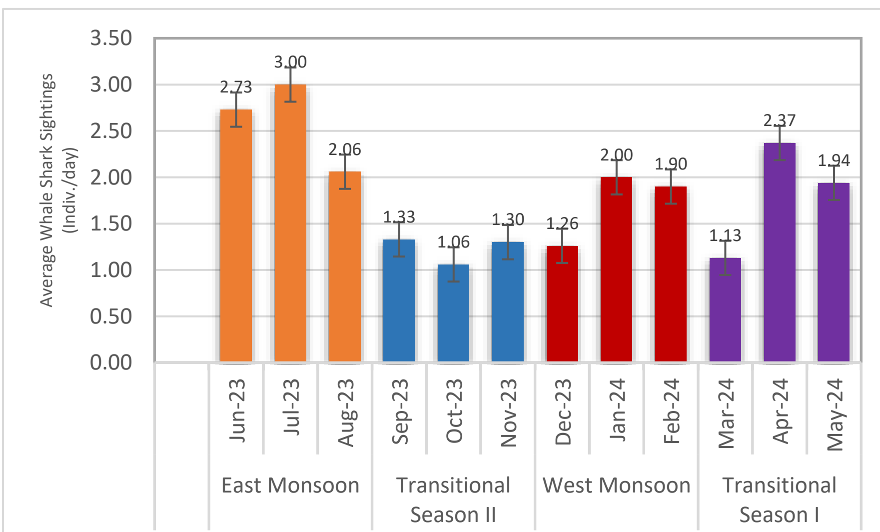

Fig. 4. Graph of monthly distribution of whale shark sightings

East monsoon

The highest occurrence of whale sharks was recorded during the eastern season, particularly in June and July, with an average of more than 2.60 individuals per day. This pattern indicates that the eastern season is a peak period of emergence for whale sharks in Botubarani Waters, a trend supported by increased primary productivity and current circulation that promote plankton aggregation—the primary food source **(Yusma *et al.*, 2024)**.

Transition season II

During the transition season II (September–November), whale shark occurrences declined sharply, with daily averages ranging from 1.06 to 1.33 individuals. This decrease is likely due to reduced chlorophyll-a concentrations and altered oceanographic dynamics affecting food distribution **(Anwar *et al.*, 2023)**. Changes in sea surface temperature and heightened anthropogenic activity during this season may also disturb the species' temporary habitat.

Western monsoon

In the Western Season (December–February), a slight increase in sightings was observed, peaking in January with nearly 2 individuals per day.

Transition season I

Sightings increased again during Transition Season I (March–May), especially in April, reaching over 2.30 individuals per day. This suggests that whale sharks exhibit migratory or ecological preferences influenced by warm sea surface temperatures and near-optimal chlorophyll-a concentrations. These findings align with studies by **Guzman *et al.* (2022)** and **Yasir *et al.* (2024)**, indicating a foraging preference for high-productivity, chlorophyll-rich areas. The movement of large marine species is strongly affected by microenvironmental conditions.

This seasonal emergence analysis is crucial for conservation-based tourism planning in Botubarani. Recognizing that the Eastern and early transitional seasons are peak periods, authorities can design sustainable tourism calendars that minimize ecological disruption. These seasonal data also enhance the accuracy of whale shark arrival predictions, improving long-term monitoring strategies and supporting adaptive conservation policies in tropical coastal regions **(Himawan *et al.*, 2022)**.

According to **Tilahunga *et al.* (2024)**, satellite tracking of two whale sharks showed consistent movement patterns within Tomini Bay, reinforcing the importance of Botubarani as part of their seasonal migration corridor.

2. Influence of oceanographic parameters on seasonal whale shark occurrence

2.1. Chlorophyll-a as a key indicator of food availability

This study confirms that chlorophyll-a concentration is a key driver in the seasonal occurrence patterns of whale sharks in Botubarani. A statistically significant positive correlation ($r = 0.63$; $P < 0.05$) was observed between chlorophyll-a levels and the average number of sightings. During the eastern season (June–August), chlorophyll-a peaked at 1.83mg/ m^3, coinciding with the highest average daily sightings (2.60 individuals). These findings support the hypothesis that whale shark aggregations are influenced by the availability of planktonic food sources.

While natural oceanographic processes largely drive this seasonal productivity, anthropogenic influences—such as nutrient runoff from coastal development and tourism—may also contribute to chlorophyll-a levels. This process, known as cultural eutrophication, can artificially alter plankton bloom timing, potentially impacting whale shark feeding behavior and the reliability of Botubarani as a foraging ground.

In contrast, during the transition season II (September–November), chlorophyll-a concentrations dropped to 0.34mg/ m³, corresponding to a sharp decrease in sightings. This highlights the dependence of whale sharks on food availability, reinforcing the importance of chlorophyll-a as a seasonal indicator of their emergence patterns. These results are consistent with findings from **Ranintyari *et al.* (2018)**.

2.2. Complexity of sea surface temperature (SST) influence

The influence of SST on whale shark emergence appears to be complex and non-linear. Although Pearson correlation analysis did not yield statistically significant results, seasonal trends suggest SST remains ecologically relevant. Peak whale shark sightings occurred during the cooler eastern season, with SSTs ranging from 27.5 to 28°C. These cooler temperatures are often linked to upwelling, which increases nutrient availability and primary productivity.

During the transition season I (March–May), SST peaked at 30.3°C. Although sightings remained high in April, such temperatures approach the upper thermal tolerance for whale sharks (23–30°C). Studies suggest that SSTs above 30°C can reduce whale shark feeding and surface presence. While some populations (e.g., in Cenderawasih Bay) tolerate warmer conditions, whale sharks in Botubarani prefer cooler, more productive waters. These findings are consistent with local observations by **Yasir *et al.* (2024)**, who reported sightings in SSTs between 28.36 and 30.29°C.

2.3. Current peed as a limiting factor

Current speed emerged as another important factor influencing whale shark presence. A significant inverse correlation was found between current speed and whale shark sightings ($r = -0.63$; $P < 0.05$). Whale sharks appear to favor calm water conditions, which facilitate plankton aggregation and allow more energy-efficient foraging. During the eastern season, current speeds averaged just 0.12m/ s, reaching a low of 0.11m/ s in July 2023.

In contrast, the highest current speeds were recorded during the western season (December–February), peaking at 0.22m/ s in February. Despite relatively high chlorophyll-a concentrations in this period, whale shark sightings did not increase comparably. This suggests that strong currents may disrupt foraging efficiency and plankton distribution. These results align with the work of **Sleeman *et al.* (2011)** and **Reinero *et al.* (2024)**, who reported that strong currents can deter whale shark aggregation, while moderate or calm currents are more favorable.

2.4. The eastern season as the optimal emergence period

The peak emergence of whale sharks during the Eastern Season is attributed to the combined effect of optimal oceanographic conditions. ANOVA analysis showed that the difference in sightings across seasons was marginally significant ($P = 0.055$), with a statistically significant pairwise difference between the eastern season and transition season II (P = 0.025), as identified by Tukey's HSD test.

The Eastern Season aligns with the highest chlorophyll-a levels, calmest current conditions, and relatively low SST—all contributing to ideal foraging conditions. In contrast, other seasons might meet one or two favorable criteria but not all simultaneously. Transition Season II, characterized by unstable water conditions and low productivity, corresponded with the fewest sightings.

3. Ecological implications, management considerations, and study limitations

These findings highlight critical ecological and managerial implications. Seasonally consistent whale shark presence confirms the importance of Botubarani Waters as a key foraging ground within Tomini Bay, potentially linked to local migratory routes **(Tilahunga *et al.*, 2024)**.

From a management perspective, these results support the development of a conservation-based ecotourism calendar. Prioritizing tourism during periods of natural whale shark emergence can enhance visitor experiences while minimizing disruptions to the species. Adaptive management strategies should focus on preserving these peak periods to maintain ecological balance and ensure the sustainability of both whale shark populations and tourism activities.

However, the study has limitations. First, it covers only one annual cycle, so multi-year monitoring is necessary to capture interannual variability and account for broader climate influences. Second, data from BPSPL Makassar (2016–2024) show that all identified individuals in Botubarani were male. This sex-based difference may be due to females favoring deeper, cooler offshore waters **(Bignell *et al.*, 2025)**. Lastly, reliance on satellite data for SST and chlorophyll-a may not fully reflect microhabitat conditions experienced by whale sharks. These limitations point to valuable directions for future research, including direct in-situ measurements and longer-term ecological monitoring.

CONCLUSION

The appearance of whale sharks in Botubarani Waters follows a consistent seasonal pattern, with a significant peak occurring during the eastern season, characterized by low temperatures, high chlorophyll-a levels, and supportive currents. This phenomenon is supported by a significant relationship between oceanographic parameters, specifically chlorophyll-a and current speed, with the frequency of whale shark emergence. Oceanographic seasons statistically affect the difference in the rate of emergence, particularly between the eastern season and the transition season II, highlighting the importance of the marine environment's dynamics in determining the existence of this species. Thus, this research provides a scientific basis for season-based tourism management that supports long-term habitat protection.

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