

## Assessment of Wave Characteristics in National Water Borders for Tactical Vessel Analysis and Maritime Security

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### KEYWORDS

*Seasonal Wave Characteristic; Bathymetry Effect; Significant Wave Height (Hsig); Wave Energy Distribution; Ship Design; Operational Reliability*

**ABSTRACT** – This study addresses the challenge of accurately representing wave conditions in Indonesian waters for ship design, where conventional standards based on North Atlantic extremes may lead to over-conservative designs. The objective is to evaluate seasonal wave characteristics in four representative regions—North Natuna Sea, Ambalat Block, Timor Sea, and Arafura Sea—and assess their implications for ship operational reliability. Hourly wind and wave data for 2025 were obtained from ERA5 reanalysis, while bathymetric information was sourced from BATNAS. Analyses included directional distribution (wind and wave rose), temporal variability of significant wave height (Hsig) and peak period (Tp), wave energy estimation using linear wave theory, and comparison between empirical data and analytical probability models via a Weibull distribution. Results show that the North Natuna Sea experiences the highest wave loading (Hsig up to 4.450 m; energy 13.316 kW/m) due to long fetch and bathymetric shoaling. Ambalat Block exhibits minimal wave energy (0.850 kW/m) despite deep waters, indicating fetch-limited growth. Timor Sea presents moderate Hsig (1.5–2.3 m) with long wave periods (>20 s) driven by swell, while Arafura Sea shows high Hsig (2.663 m) and energy (5.526 kW/m), though shallow-water effects limit wave growth and increase wave steepness. These findings demonstrate that wave loading is controlled not only by height, but also by period and bathymetric transformation. Incorporating site-specific and seasonal wave characteristics is essential for realistic and efficient ship design and operational assessment.

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## INTRODUCTION

The geographical setting of Indonesia places the country in a strategic position for maritime transportation, national logistics distribution, and maritime surveillance [1]. Various threats are encountered especially in several national maritime border regions, including the North Natuna Sea [2], Ambalat Block [3], Timor Sea [4], and Arafura Sea [5]. The high intensity of maritime activities highlights the importance of understanding oceanographic conditions to support both the safety and operational effectiveness of vessels, particularly high-speed craft, which are highly sensitive to changes in wave conditions.

Wave characteristics in Indonesian waters are generally governed by the Asian–Australian monsoon system, which undergoes periodic changes throughout the year [6]. This monsoon system consists of the West Monsoon (December–February), Transition 1 (March–May), East Monsoon (June–August), and Transition 2 (September–November) [7]. Seasonal wind patterns induce significant variations in wave height, period, and direction, which in turn lead to differences in wave energy throughout the year. Therefore, a seasonal-based analysis is considered more representative than an approach relying solely on a single extreme value.

Wave studies in Indonesian waters commonly employ significant wave height (Hsig) as a primary parameter to describe sea conditions. Although this parameter is essential in representing general wave conditions, overall wave characteristics are also influenced by the peak wave period (Tp) and wave direction [8]. The combination of these three parameters determines the magnitude of wave energy, which is physically proportional to the square of wave height [9], [10]. Consequently, an increase in wave height results in a quadratic increase in wave energy, meaning that even small changes in wave height can produce significant increases in energy. This condition directly affects the dynamic response of vessels and the cyclic loads experienced during operation [11], [12], [13].

In ship design and operation, wave characteristics acting on the hull are a key factor in determining structural reliability and operational comfort [14]. High-speed vessels are generally designed based on specific wave conditions, taking into account stability and safety considerations [15]. However, design standards adopted by international classification societies are typically based on extreme sea conditions, such as those in the North Atlantic Ocean, which may lead to overly conservative designs when applied to waters with relatively lower wave characteristics, such as Indonesia [16]. Furthermore, differences in approaches among classification societies such as BKI, which tends to produce thicker plating, and DNV (Det Norske Veritas), which is generally more structurally efficient indicate that ship design is strongly influenced by the assumed wave environment [17]. In this context, there is a need for reassessment of wave characteristics in Indonesian waters using actual environmental data to better represent operational conditions.

Despite this, studies that directly link actual wave characteristics in Indonesian waters to their implications for vessel operational reliability remain limited, particularly those considering seasonal variability and the influence of bathymetric conditions on wave transformation processes such as shoaling, refraction, and energy dissipation [18]. In addition, variations in the combination of wind, fetch, and seabed morphology can produce distinct wave characteristics in different regions, which subsequently affect wave energy levels and vessel hydrodynamic responses. Therefore, this study is positioned as a data driven review and comparative assessment of wave characteristics across representative Indonesian waters.

Based on this gap, this study aims to analyze the seasonal wave characteristics in these four regions by considering significant wave height (Hsig), peak wave period (Tp), dominant wave direction, as well as their relationship with wind patterns and local bathymetric conditions. The study emphasizes a reassessment of existing assumptions through secondary data analysis rather than primary experimental investigation. Through this approach, the study is expected to provide a more comprehensive understanding of seasonal oceanographic dynamics in Indonesia water borders, while also elucidating their implications for the operational conditions and dynamic response of high-speed vessels used in military mission.

## METHODS

This study covers four marine regions representing the major sectors of Indonesia, namely the North Natuna Sea (western sector), Ambalat Sea (northern sector), Timor Sea (southern sector), and Arafura Sea (eastern sector), as pointed out with red dots in Figure 1. The selection of these locations was based on differences in geographical and oceanographic characteristics influenced by the Asian–Australian monsoon system, as well as the bathymetric conditions in each region.

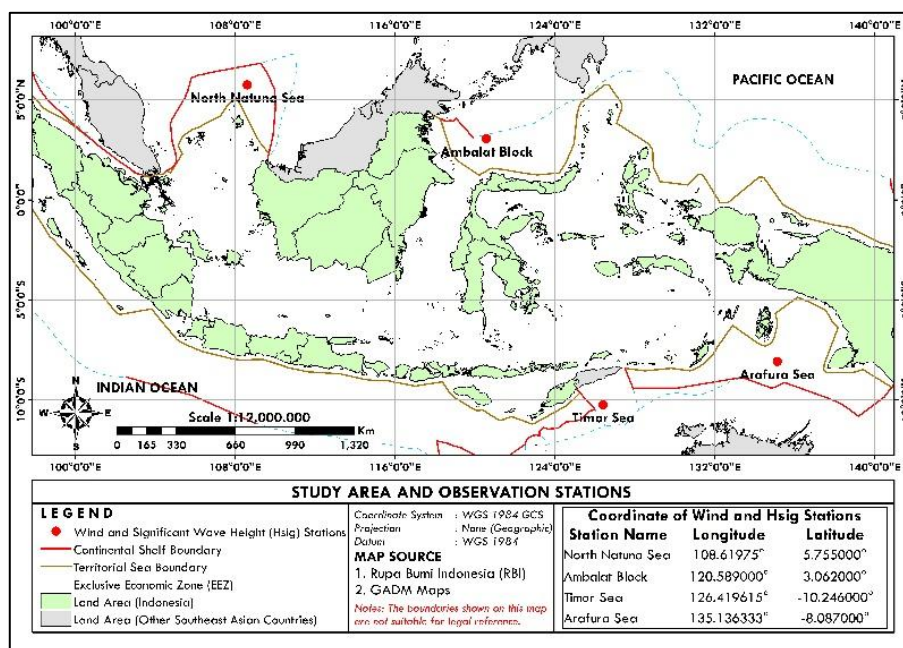
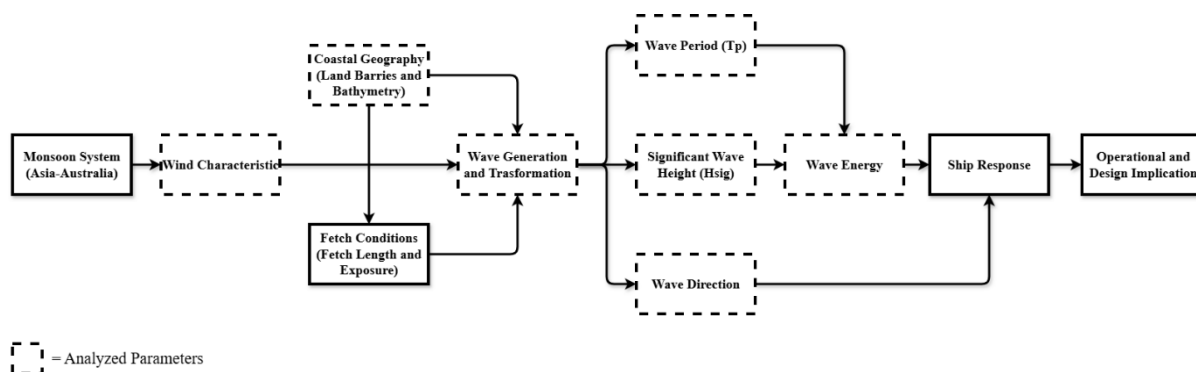


Figure 1. Research map location



**Figure 2.** Conceptual framework linking monsoon driven wave generation to patrol vessel response

To provide a systematic basis for the analysis, this study adopts a conceptual framework that describes the physical linkage between wave generation processes and ship response, as illustrated in Figure 2. The Asian–Australian monsoon system acts as the primary driver controlling wind characteristics, including direction, speed, and seasonal consistency [19]. These wind conditions serve as the main mechanism for wave generation [20], where the effectiveness of energy transfer from wind to the sea surface is influenced not only by wind properties but also by fetch conditions, representing the length and openness of the wind path over the sea surface [21]. Furthermore, geographical configuration and bathymetric features play a crucial role in modifying wave generation and transformation processes through mechanisms such as shoaling, refraction, and energy dissipation [18]. These interactions are represented by key wave parameters, namely significant wave height ( $H_{sig}$ ), peak wave period ( $T_p$ ), and wave direction. In terms of wave energy, the combination of  $H_{sig}$  and  $T_p$  determines the magnitude of transmitted energy, with wave height acting as the dominant factor [22]. Subsequently, wave energy and wave direction govern the dynamic response of vessels, where energy reflects the magnitude of hydrodynamic loads [15], while wave direction determines the orientation of wave–ship interaction [23]. The integration of these factors provides the basis for evaluating operational and design aspects of patrol vessels, highlighting the importance of a wave-based approach that reflects actual ocean conditions in Indonesian waters. This framework underpins the selection of datasets and analytical approaches used in this study.

Surface wind data and wave parameters were obtained from the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset covers the period from January to December 2025 with hourly temporal resolution. Sampling points were selected using a purposive approach to ensure representative offshore conditions while avoiding extreme local influences, such as narrow coastal areas or enclosed waters. The analyzed wave parameters include significant wave height ( $H_{sig}$ ), peak wave period ( $T_p$ ), and dominant wave direction. Wind data were further utilized to examine wave generation patterns and their relationship with seasonal variability in the study areas.

Bathymetric data were obtained from the National Bathymetry dataset (BATNAS) and used to evaluate the influence of seabed depth on wave transformation processes. The bathymetric analysis aimed to identify morphological characteristics of the waters, such as shallow and deep-water regions, which play an important role in wave transformation processes including shoaling, refraction, and energy dissipation.

The analysis was conducted based on the Indonesian monsoon classification, consisting of the West Monsoon (December–February), Transition 1 (March–May), East Monsoon (June–August), and Transition 2 (September–November). Wind and wave direction distributions were analyzed using rose diagrams to identify dominant directions and frequency of occurrence. In addition, time series analysis was performed to evaluate the temporal variability of  $H_{sig}$  and  $T_p$  on both annual and seasonal scales.

Wave energy estimation was conducted using linear wave theory, where the wave energy per unit area is expressed as follows [24], [25]:

$$E = \frac{\rho g^2}{32\pi} H_{sig}^2 T_p \quad (1)$$

Where  $E$  is the wave energy flux (kW/m),  $\rho$  is the seawater density,  $g$  is the gravitational acceleration,  $H_{sig}$  is the significant wave height, and  $T_p$  is the wave period. This approach was used to assess the spatial distribution of wave energy across the study regions. Furthermore, wave energy was employed as a preliminary indicator to evaluate the potential dynamic loads acting on ship structures. This analysis forms the basis for assessing the implications of wave conditions on the operational response of high-speed vessels, particularly in the context of operational reliability in Indonesian waters. To facilitate comparison between the wave data used in limit-state ship design [26] and field-based observations, a Weibull distribution was applied [27]. This distribution smooths

empirical observations into a Probability Density Function (PDF), if the data follows a continuous theoretical curve governed by statistical parameters. The Weibull distribution is expressed as:

$$f(H_s) = \frac{k}{\lambda} \left(\frac{H_s}{\lambda}\right)^{k-1} \exp \left[-\left(\frac{H_s}{\lambda}\right)^k\right] \quad (2)$$

where  $f(H_s)$  represents the probability density of a given significant wave height,  $k$  is the shape parameter (taken as 2), and  $\lambda$  is the scale parameter.

## RESULTS AND DISCUSSION

### Influence of Bathymetry on Wave Characteristics

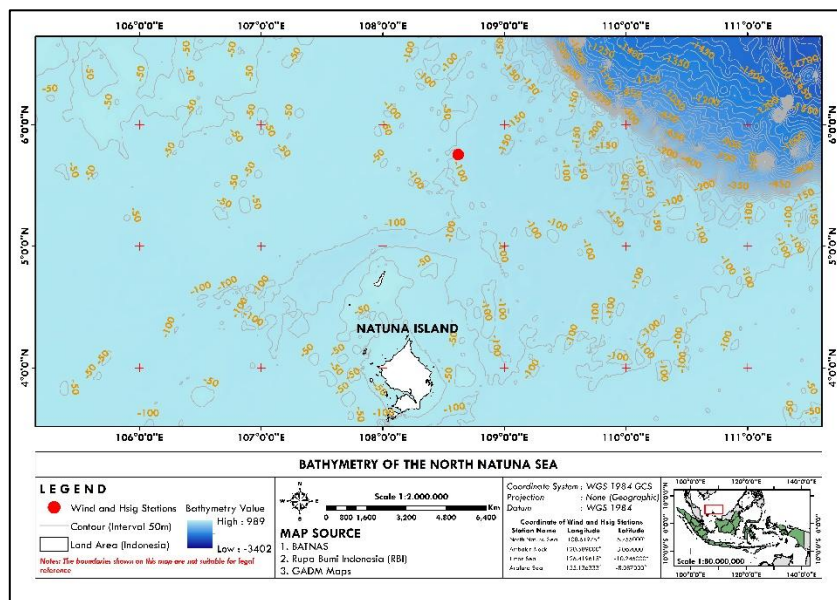


Figure 3. Bathymetry of the North Natuna Sea

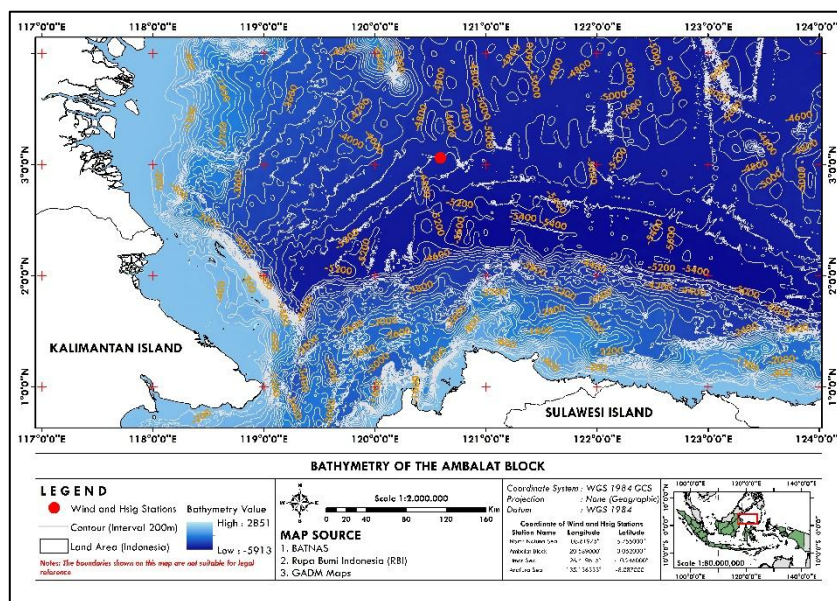


Figure 4. Bathymetry of the Ambalat Block

Based on the bathymetric analysis of the four marine regions (Figures 3–6), significant variations in seabed morphology can be observed, both in terms of depth and topographic gradients. In the North Natuna Sea, the seabed morphology is characterized by shallow zones around the Natuna Islands (50–100 m), which gradually transition into deeper waters toward the northeast (>1000 m). The observation station, located within this

transitional zone, causes waves propagating from the South China Sea to undergo shoaling due to decreasing depth [28], as well as refraction due to changes in seabed contours [29]. These conditions indicate that wave characteristics in this region result from a combination of wind-generated processes and bathymetric transformation.

In the Ambalat Block, the bathymetry is dominated by deep waters, with depths exceeding 4000 m around the observation area, while shallow waters are limited to the coastal zones of Kalimantan and Sulawesi. This deep-sea environment reduces the influence of the seabed on wave development [30], so wave evolution is primarily controlled by wind generation and fetch length. Therefore, wave characteristics in this region are more representative of wind-generated conditions rather than bathymetric transformation.

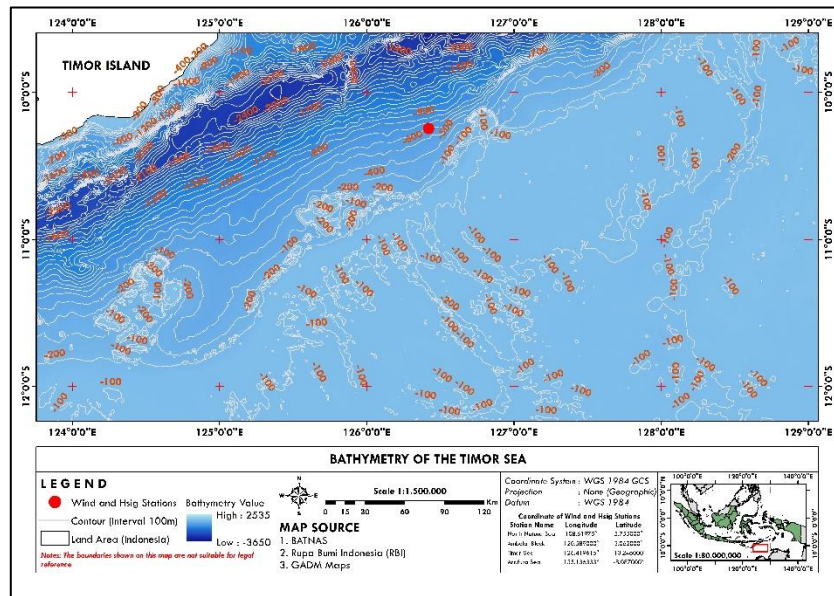


Figure 5. Bathymetry of the Timor Sea

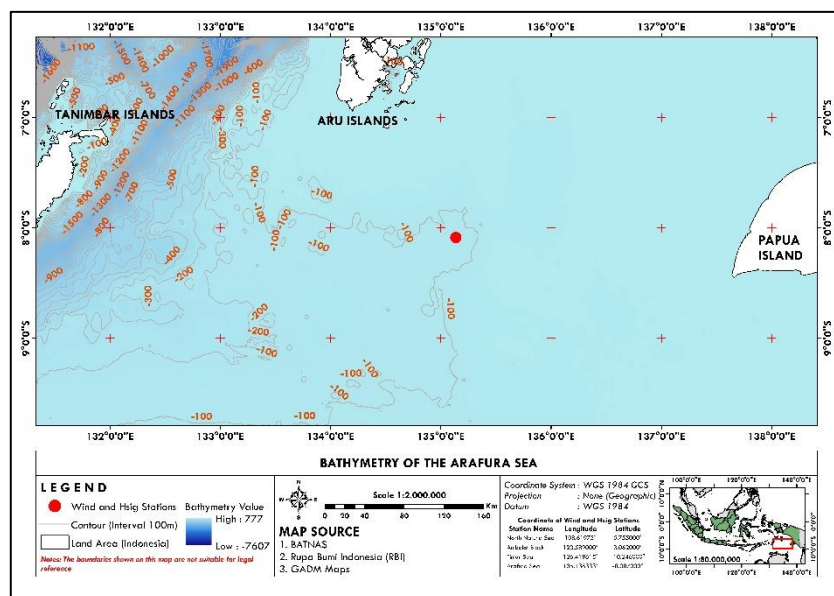


Figure 6. Bathymetry of the Arafura Sea

In the Timor Sea, the bathymetry exhibits a complex morphology, including the presence of a deep-sea basin in the southern part of Timor Island, where depths can exceed 2000 m. From this zone, the seabed gradually becomes shallower toward the south, approaching the Australian continental shelf with depths of up to 100 m. The observation station, located at a depth of approximately 600 m, lies within a transitional zone. Under these conditions, waves may experience changes in their characteristics along their propagation path, particularly when entering shallower waters where interaction with the seabed increases [31]. In addition, steep topographic gradients enhance wave refraction and energy redistribution [32].

Meanwhile, the Arafura Sea is dominated by a shallow continental shelf, with depths generally less than 100 m, including at the observation station. This condition leads to stronger wave–seabed interaction, making shoaling processes and energy dissipation due to bottom friction dominant [33], [34]. As a result, wave growth tends to be limited and is primarily influenced by shallow-water conditions. Although deeper basins are present around the Tanimbar Islands (1000–1900 m), their influence on the observation point is relatively minor.

Overall, these differences in bathymetric characteristics indicate that wave responses to wind forcing are not uniform across regions. Deep-water environments such as the Ambalat Block allow waves to develop with minimal seabed influence, whereas shallow-water environments such as the Arafura Sea are more strongly affected by wave–seabed interaction. Transitional regions, such as the North Natuna Sea and the Timor Sea, exhibit a combination of wind-generated processes and bathymetric transformation. These differences ultimately influence the characteristics of wave-induced loads acting on vessels.

### Wind Distribution Characteristics

The dynamics of wave systems in Indonesian waters are generally influenced by the Asian–Australian monsoon wind system, which produces variations in wind patterns with differing directions and intensities throughout the year. This pattern is formed due to differences in atmospheric pressure between the Asian and Australian continents, which vary seasonally following the annual cycle of solar heating [19], [35]. These pressure differences cause a seasonal reversal of wind direction, where the West Monsoon is dominated by airflow from Asia toward Australia, while the East Monsoon exhibits the opposite pattern [36]. These variations in wind patterns play a direct role in wave generation as the primary mechanism for energy transfer to the sea surface [20]. The wind rose results in Figure 7 show that wind patterns across the four regions are generally bidirectional, characterized by two dominant opposing directions, reflecting seasonal variability associated with the monsoon system.

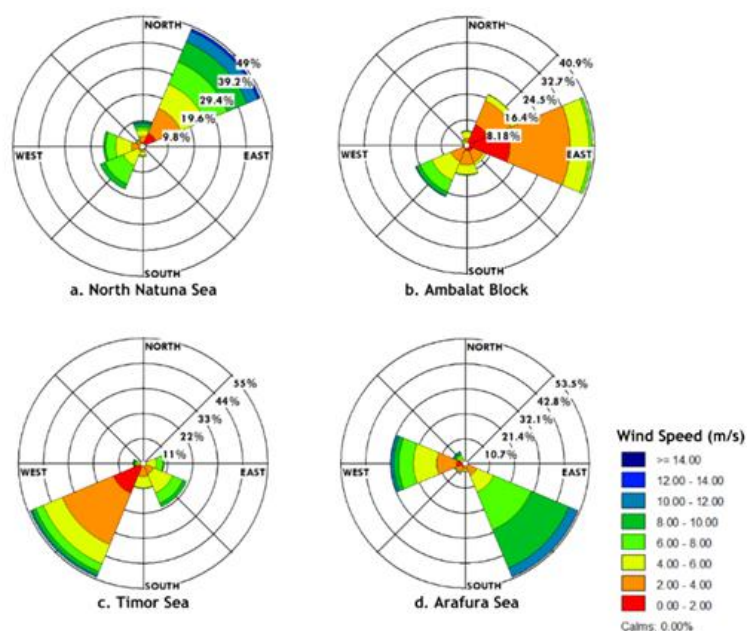


Figure 7. Wind rose diagram for selected Indonesia waters

In the North Natuna Sea, dominant winds originate from the northeast, with secondary contributions from the southwest to west. Although a bidirectional pattern is observed, the northeast direction is more effective in generating waves due to the presence of a long, unobstructed fetch from the South China Sea. In contrast, winds from the west and southwest are limited by land barriers, which reduce fetch length and wind energy [37]. This condition results in wave generation being concentrated in a single dominant direction. In the Ambalat Block, dominant winds originate from the east, with secondary contributions from the southwest. In general, wave generation in this region is influenced not only by the dominant wind direction but also by fetch limitations caused by surrounding land configurations. The eastern direction provides a more open fetch toward the Sulawesi Sea, making it more effective for wind-driven wave generation, while other directions are less developed. As a result, the wind energy transferred to the sea surface remains relatively limited, even though the region is characterized by deep-water conditions.

Unlike the other regions, the Timor Sea exhibits a wind pattern dominated by directions from southern Indonesia (southwest and southeast), which are relatively consistent. This directional consistency indicates that

wave generation occurs more steadily, as wind variability is limited. The open exposure to the Indian Ocean also allows for a very long fetch, enabling winds not only to generate local waves but also to enhance the propagation of swell from the open ocean. Meanwhile, the Arafura Sea shows a bidirectional pattern with a dominant contribution from the southeast. This direction serves as the primary driver of wave generation due to its long fetch over a broad continental shelf. However, despite the relatively long fetch, shallow-water conditions limit the full development of wave energy, as part of the energy is dissipated through interaction with the seabed.

In addition to wind direction, wind speed distribution also plays an important role in determining the intensity of wave generation, as the energy transferred to the sea surface increases with wind speed and duration [38]. Therefore, the combination of effective wind direction (fetch) and wind speed characteristics becomes the main factor controlling wave variability in each region. Overall, differences in wind patterns across the four regions indicate that wave generation is influenced not only by dominant wind direction, but also by directional consistency and available fetch length. Regions with stable wind directions and long fetch tend to produce more developed waves [21], whereas regions with more variable wind directions tend to exhibit more fluctuating wave conditions [6].

### Characteristics of Significant Wave Height (Hsig)

Based on the Hsig rose diagram results (Figure 8), the wave direction patterns in the four regions exhibit a bidirectional tendency that follows the dominant wind directions. However, the main differences between regions lie not only in wave direction, but also in the magnitude of Hsig and the range of wave periods (Tp), as presented in Table 1 and Table 2, which directly represent differences in wave energy.

In the North Natuna Sea, waves are predominantly generated from the northeast, with secondary contributions from the southwest to west. This condition is influenced by the open exposure to the South China Sea, which provides a long, unobstructed fetch. Temporal analysis (Figure 9) shows that the maximum Hsig occurs during the West Monsoon, reaching 4.450 m, then decreases during Transition 1 and gradually increases again toward the following West Monsoon. Based on Table 1, Hsig values in this region are the highest among all locations, indicating strong wave energy dominance. Meanwhile, the wave period values in Table 2 show a relatively wide range, with differences between minimum and maximum values indicating a combination of locally generated waves and swell contributions from the open sea. These conditions indicate that wave dynamics in the North Natuna Sea are controlled by the West Monsoon, supported by long fetch and bathymetric transformation effects.

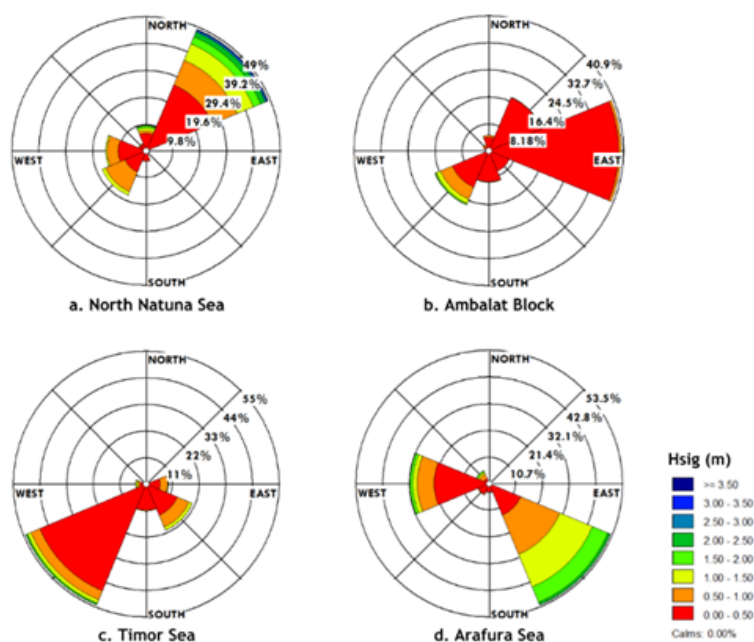


Figure 8. Significant wave height rose diagram for selected Indonesian waters

In the Ambalat Block, the dominant wave direction originates from the east, with secondary contributions from the southwest. This is related to the openness toward the Sulawesi Sea on the eastern side, while the western direction is blocked by the Kalimantan landmass, limiting effective fetch. Temporal analysis (Figure 10) indicates that Hsig remains relatively low and stable throughout the year, with increases occurring during the East Monsoon and Transition 2. The maximum Hsig reaches 2.223 m, while the average values in Table 1 indicate generally lower wave conditions compared to other regions. The Tp values in Table 2 show a relatively narrow range

compared to other regions, indicating the dominance of locally generated waves due to limited fetch. Although this region is characterized by deep water, wave characteristics are more controlled by limitations in wind generation rather than bathymetric influence.

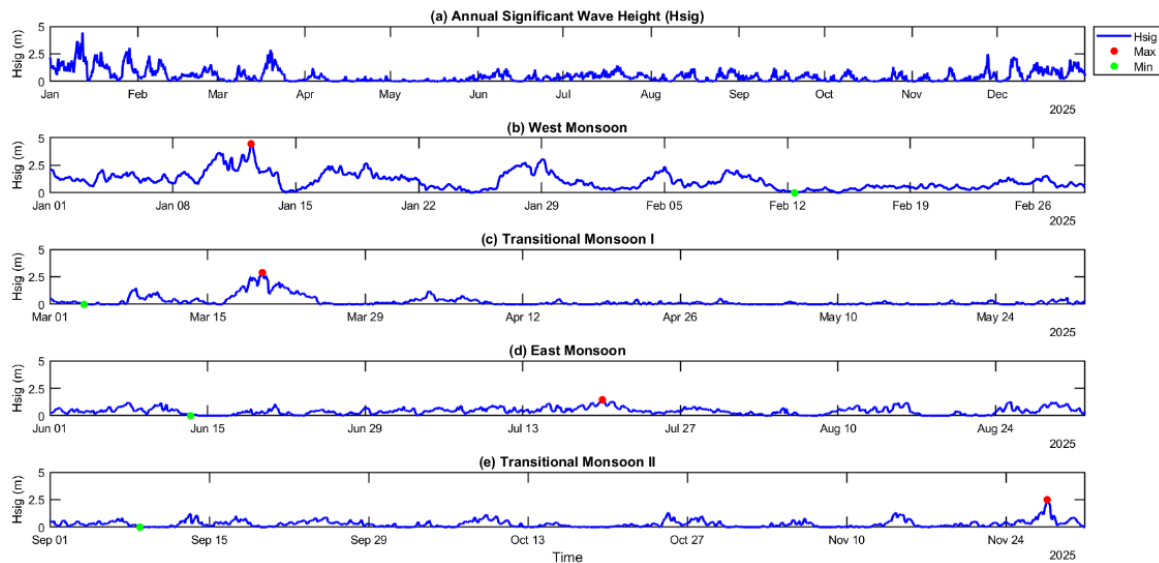


Figure 9. Annual and seasonal variability of significant wave height in the North Natuna Sea

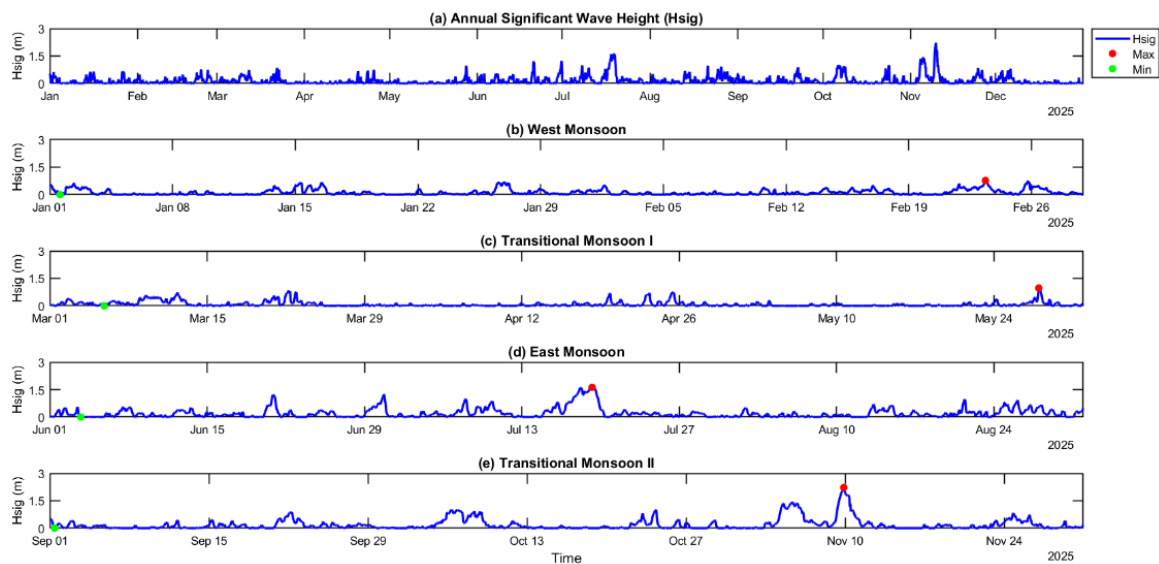


Figure 10. Annual and seasonal variability of significant wave height in the Ambalat Block

In the Timor Sea, wave directions are dominated by the southwest and southeast, reflecting the direct influence of the Indian Ocean. The very long fetch from the southwest allows the formation of high-energy waves as well as swell contributions from the open ocean. Temporal analysis (Figure 11) shows that Hsig remains relatively stable throughout the year, with more consistent increases during the East Monsoon. The maximum Hsig ranges between 1.5 and 2.3 m. Based on Table 2, the wave period range shows maximum values exceeding 20 seconds, indicating significant swell contributions from the open ocean. Thus, although wave heights are lower than those in the North Natuna Sea, wave energy remains significant and may influence vessel motion responses.

Meanwhile, in the Arafura Sea, wave directions are dominated by the southeast, associated with the East Monsoon winds. Temporal analysis (Figure 12) shows that the most consistent increase in Hsig occurs during the East Monsoon, with a maximum value reaching 2.663 m, while other seasons remain relatively lower and stable. Based on Table 1, Hsig values in this region are relatively high but do not develop to extreme levels. This is related to shallow bathymetric conditions that limit wave growth. The Tp values in Table 2 indicate a relatively smaller range compared to other regions, where lower maximum values reflect the dominance of locally generated waves. Strong interaction with the seabed also leads to significant energy dissipation, further limiting wave development.

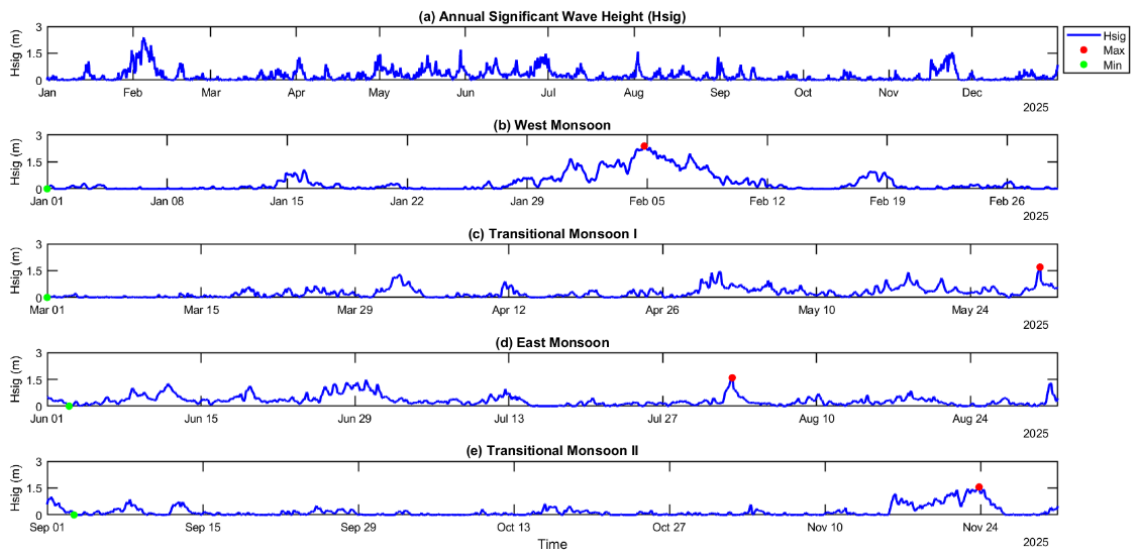


Figure 11. Annual and seasonal variability of significant wave height in the Timor Sea

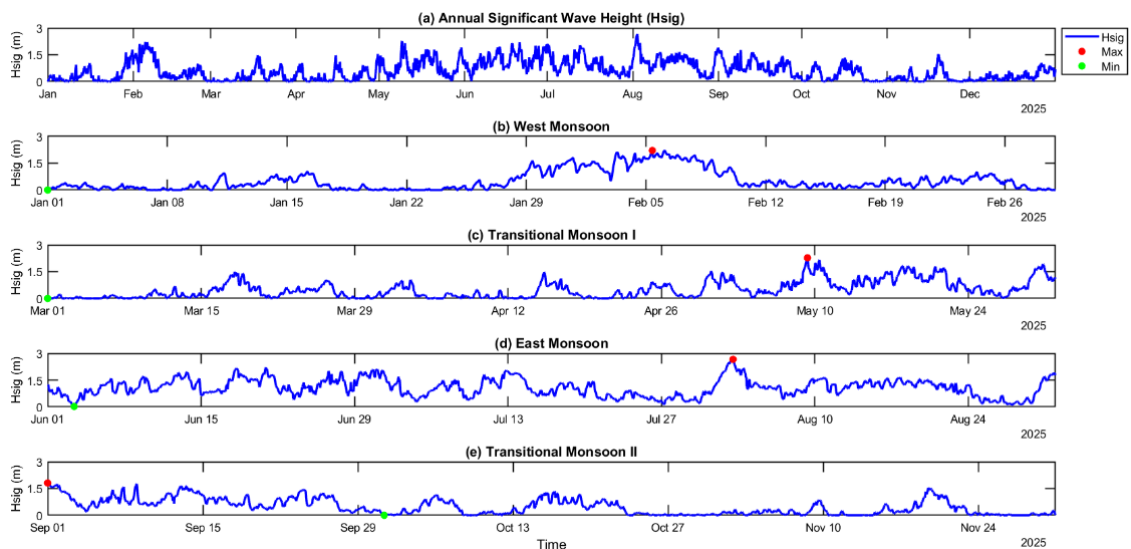


Figure 12. Annual and seasonal variability of significant wave height in the Arafura Sea

Table 1. Maximum and minimum Hsig (m) in selected Indonesia waters

| Monsoon      | North Natuna Sea |       | Ambalat Block |       | Timor Sea |       | Arafura Sea |       |
|--------------|------------------|-------|---------------|-------|-----------|-------|-------------|-------|
|              | Max              | Min   | Max           | Min   | Max       | Min   | Max         | Min   |
| West         | 4.450            | 0.000 | 0.776         | 0.000 | 2.389     | 0.000 | 2.217       | 0.000 |
| Transition 1 | 2.881            | 0.000 | 0.969         | 0.000 | 1.698     | 0.000 | 2.275       | 0.000 |
| East         | 1.448            | 0.000 | 1.621         | 0.000 | 1.588     | 0.000 | 2.663       | 0.021 |
| Transition 2 | 2.496            | 0.000 | 2.223         | 0.000 | 1.560     | 0.000 | 1.811       | 0.000 |

Table 2. Maximum and minimum Tp (s) in selected Indonesia waters

| Monsoon      | North Natuna Sea |       | Ambalat Block |       | Timor Sea |       | Arafura Sea |       |
|--------------|------------------|-------|---------------|-------|-----------|-------|-------------|-------|
|              | Max              | Min   | Max           | Min   | Max       | Min   | Max         | Min   |
| West         | 11.643           | 5.831 | 10.870        | 3.684 | 19.350    | 4.219 | 10.163      | 2.703 |
| Transition 1 | 10.270           | 2.785 | 13.502        | 3.001 | 18.960    | 3.848 | 13.367      | 2.715 |
| East         | 8.865            | 2.484 | 10.634        | 2.372 | 17.558    | 3.438 | 8.376       | 4.222 |
| Transition 2 | 14.614           | 2.726 | 17.529        | 2.498 | 20.074    | 3.769 | 17.456      | 2.858 |

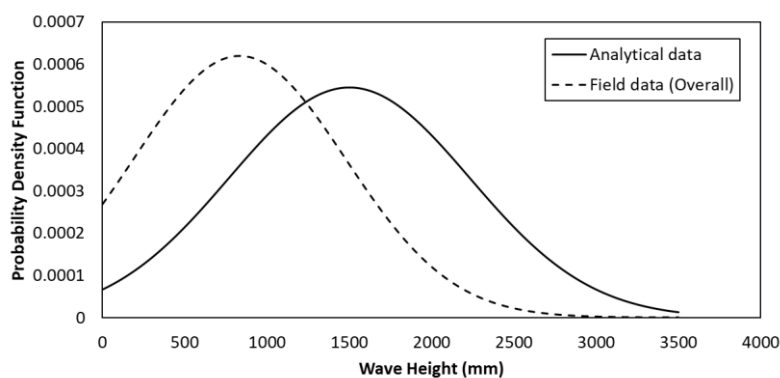
Overall, the Hsig characteristics across the four regions indicate that wave generation and development are controlled by a combination of seasonal wind patterns, fetch length, and bathymetric conditions. Longer and more persistent fetch allows more efficient transfer of wind energy to the sea surface, resulting in higher wave energy

[39], while bathymetric conditions modify wave characteristics through transformation processes such as shoaling, refraction, and energy dissipation [18], [40], [41]. This is evident in open waters such as the North Natuna Sea and the Timor Sea, which tend to produce more developed waves, compared to the Ambalat Block, which, despite being a deep-water region, still exhibits relatively low wave energy due to limited effective fetch. In contrast, shallow waters such as the Arafura Sea show limited wave growth due to seabed influence. These differences directly affect vessel operational conditions, where wave height, period, and directional consistency influence vessel motion responses such as heave and pitch [42].

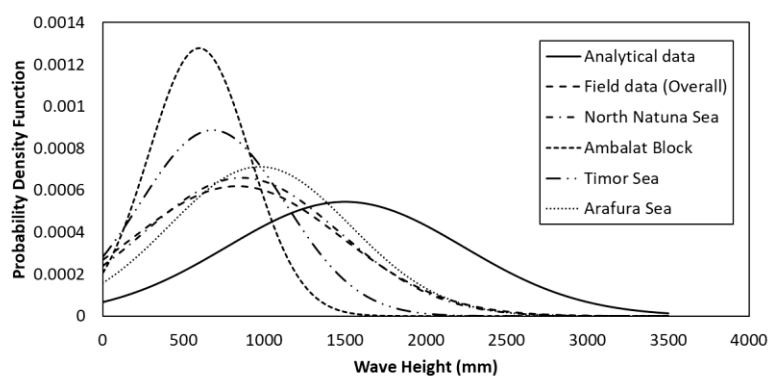
Based on the probability density function (PDF) analysis, a significant difference is observed between the empirical distribution derived from field data and the analytical model curve. The empirical distribution indicates that actual sea conditions are consistently dominated by low waves, as represented by a left-skewed distribution. In contrast, the analytical theoretical curve produces a much broader and more uniform distribution of probability, resulting in an artificially higher probability of extreme wave events.

In the context of structural design, the analytical approach tends to be overly conservative. It produces overestimated environmental load predictions, which directly lead to higher required design parameters. As a consequence, the design may result in over-engineering, where structures require thicker dimensions, higher-grade material specifications, and increased construction costs. Therefore, outputs derived directly from empirical field data distributions are considered more representative and optimal for producing efficient yet functional structural designs that reflect actual operational conditions.

This argument is further supported by regional variability analysis, where all observation locations confirm the dominance of relatively calm sea conditions. The Ambalat Block and the Timor Sea consistently show the highest probability peaks within the low wave range (500–600 mm). The North Natuna Sea exhibits moderate conditions, with most waves occurring within the range of 800–900 mm. Although the Arafura Sea shows the widest distribution, with a peak at 1000–1100 mm, the observed values remain significantly lower than the extreme estimates suggested by the analytical curve. These findings reinforce the conclusion that designs based on empirical field data probabilities provide more realistic construction efficiency compared to conventional analytical models.



**Figure 13.** Comparison of analytical and empirical wave probability distributions



**Figure 14.** Comparison of analytical and empirical wave probability distributions for each marine region

### Wave Energy Distribution

The results of the monthly wave energy analysis (Figure 15 and Table 3) indicate that wave energy distribution across the four regions is highly variable and influenced by seasonal variability. This pattern is consistent with

the distribution of wind and Hsig, where wave energy is governed by the combined effect of wave height and wave period [22]. Therefore, differences in wave energy between regions are not solely determined by the magnitude of Hsig, but also by the characteristics of the wave period.

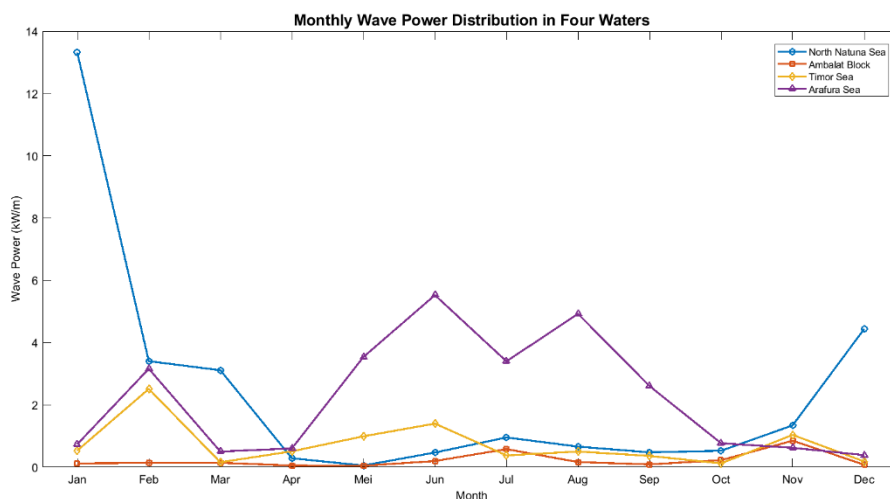


Figure 15. Monthly wave power distribution in selected Indonesia waters

Table 3. Average and maximum wave power in selected Indonesia waters

| Indonesia Waters | Average (kW/m) | Maximum (kW/m) |
|------------------|----------------|----------------|
| North Natuna Sea | 2.421          | 13.316         |
| Ambalat Block    | 0.225          | 0.850          |
| Timor Sea        | 0.724          | 2.513          |
| Arafura Sea      | 2.231          | 5.526          |

In the North Natuna Sea, wave energy shows strong dominance during the West Monsoon, with a maximum value reaching 13.316 kW/m in January and an annual average of 2.421 kW/m. This condition reflects the combined influence of long fetch and strong monsoonal winds from the northeast. In addition, the presence of a transitional bathymetric zone from deep to shallow waters enhances shoaling processes, which increase wave height during propagation [43], [44]. This combination results in high wave energy, implying increased dynamic loads on vessels, particularly during the West Monsoon period.

In the Ambalat Block, wave energy remains relatively low, with an annual average of 0.225 kW/m and a maximum of 0.850 kW/m. Although this region is characterized by deep water, the generated wave energy remains limited. This indicates that wind generation is the primary controlling factor, where wind speed and duration are insufficient to produce high-energy waves. Effective fetch develops only from certain directions, while other directions are constrained by surrounding land configurations. As a result, wave conditions in this region tend to be calmer and more stable, leading to lower wave-induced loads on vessels.

In the Timor Sea, wave energy reaches a maximum value of 2.513 kW/m, with an annual average of 0.724 kW/m. Seasonally, increases in energy are observed during the West Monsoon and Transition Season I. Although wave heights are lower than those in the North Natuna Sea, the presence of long wave periods due to swell contributions from the Indian Ocean results in significant wave energy. This indicates that even moderate wave heights, when associated with long-period waves, can significantly influence vessel motion responses such as pitching and heaving.

Meanwhile, in the Arafura Sea, wave energy shows a relatively high annual average of 2.231 kW/m, with a maximum value reaching 5.526 kW/m, particularly during the East Monsoon and Transition Season I. However, the dominance of shallow-water conditions leads to strong wave-seabed interaction. Processes such as bottom friction and wave breaking cause energy dissipation, thereby limiting wave growth. In addition, wave transformation in shallow waters tends to increase wave steepness, which may elevate the risk of slamming on vessels [42].

Overall, the distribution of wave energy across the four regions indicates that the interaction between wind, fetch, and bathymetry produces distinct wave energy characteristics. The North Natuna Sea is dominated by high energy due to the combination of strong winds and long fetch, the Ambalat Block exhibits low energy due to limited wind generation, the Timor Sea is influenced by swell contributions with long periods, while the Arafura Sea shows energy limitations due to dissipation in shallow waters. These differences not only affect the magnitude of wave energy but also influence vessel response characteristics, making them an important factor in evaluating the safety and operational performance of patrol vessels.

## CONCLUSION

Based on the analysis results, wave characteristics in Indonesian waters are controlled by the interaction between monsoonal winds, fetch length, and bathymetric conditions, resulting in significant differences across regions. The North Natuna Sea exhibits the most energetic conditions, with a maximum Hsig reaching 4.450 m and wave energy up to 13.316 kW/m, influenced by long fetch from the South China Sea and enhanced shoaling within the transitional zone. In contrast, the Ambalat Block represents the calmest conditions, with a maximum Hsig of 2.223 m and wave energy of only about 0.850 kW/m, indicating that despite being a deep-water region, limited effective fetch results in low wave generation. The Timor Sea shows a distinct characteristic, where Hsig is relatively moderate (1.5–2.3 m), but wave periods are long (exceeding 20 seconds) due to swell contributions from the Indian Ocean. As a result, wave energy remains significant (2.513 kW/m) and has the potential to increase vessel dynamic responses. Meanwhile, the Arafura Sea exhibits relatively high Hsig (2.663 m) with wave energy reaching 5.526 kW/m; however, wave growth is limited by shallow bathymetric conditions, which promote energy dissipation while simultaneously increasing wave steepness.

These differences confirm that wave height does not always directly represent wave energy, as wave period and bathymetric transformation processes also play critical roles. In the context of naval architecture, wave conditions characterized by high energy and long periods tend to increase dynamic loads and vessel motion responses, whereas in shallow waters, wave steepness becomes the dominant factor that may elevate the risk of slamming. Therefore, this study highlights the importance of a data driven reassessment of wave characteristics based on actual environmental conditions and seasonal variability, providing a more realistic basis for evaluating vessel operation and design in Indonesian waters compared to conventional approaches relying on extreme ocean conditions.

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