Wave Characteristics in the Northern Waters of Central Java Based on the Wavewatch III Numerical Model

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Abstract

The northern coast of Central Java is a strategic development area, yet prone to coastal hazards, such as high waves. Planning activities and mitigating maritime disaster risks requires an understanding of wave characteristics. This study analyzes wave characteristics in the northern waters of Central Java using the Wavewatch III numerical model. Significant wave height and wave direction were averaged from 2014 to 2023. The results showed that wave height in the northern waters of Central Java tends to be higher during the active phase of Asian and Australian monsoons in December, January, February, July, August, and September. Maximum significant wave height during these active seasons is 1.2 m. Meanwhile, significant wave height recorded at maximum of 0.8 m during the low season. The wave direction is from the west-northwest in December to March, then reverses to the east-northeast in April to November.

Keywords: *coast of java, wave height, Central Java, numerical model, Wavewatch III*

INTRODUCTION

The northern coast of Central Java has been a strategic development area since the 19th century. This region has evolved into a center of economic activity and a major transportation route on the island of Java, underscoring its important role as a hub for commodity shipping and business (Dick et al., 2002). However, Northern Coast of Central Java faces many potential natural disasters, such as high waves (Marfai *et al*., 2020). High waves affect human life, especially disruptions to ship navigation, fishing activities, port operations, and offshore operation (Kurniawan, Habibie, & S.Permana, 2012; Ponce de León & Guedes Soares, 2021; Rajapakse & Emad, 2023; WMO, 2011).

Understanding the spatial and temporal patterns of wave regimes along the coastlines is important to mitigate the risk caused by high waves (Ardhuin *et al*., 2019). Due to the limited availability of in-situ wave measurements in most regions, such as Northern Waters of Central Java, numerical simulations are essential for providing long-term wave data (Akpınar & Bingölbali, 2016; Amarouche *et al*., 2018; Musić & Nicković, 2008). Numerical models have become the main instrument in operational wave prediction since they were first developed, along with the advancement of wave theory and computer technology (Inoue, 1967; Smyth *et al*., 2001; Tolman, 2010).

Previous studies have provided a general overview of wave height characteristics using numerical models in Indonesian waters (Efendi *et al*., 2023; Kurniawan, Habibie, & Permana, 2012; Kurniawan & Khotimah, 2016; Purwanto *et al*., 2021; Rachmayani *et al*., 2018; Ribal *et al*., 2020) and the Java Sea (Nugroho *et al*., 2022) which concluded that high waves generally occur during the active phase of the Asian and Australian monsoons. These overviews often lack attention to local

Diterima/Received: 28-09-2024, Disetujui/Accepted: 28-10-2024
DOI: https://doi.org/10.14710/jkt.v27i3.24850

details since some coasts receive lower waves due to protection from coral reefs, islands or headlands (Ghanavati et al., 2024; Short, 2020).

This study aims to characterize significant wave height and wave direction in the Northern Waters of Central Java. Understanding wave characteristics provides essential insights for mitigating hazards and optimizing marine operations. The specific research area, known for its complex coastline (Adytia *et al*., 2022), allows for a detailed examination of wave characteristics. This study uses wave hindcast datasets from the Wavewatch III numerical model, covering the period from 2014 to 2023.

MATERIAL AND METHODS

This research was conducted in the North Waters of Central Java as described in Figure 1. In total, the study area encompasses 13 regencies and cities that directly border the North Waters of Central Java, including Brebes, Tegal City, Tegal, Pemalang, Pekalongan, Pekalongan City, Batang, Kendal, Semarang City, Demak, Jepara, Pati, and Rembang.

The data used in this study consists of in situ wave measurement and WW3 model data. In situ wave measurements were conducted using an Acoustic Doppler Current Profiler (ADCP) placed at coordinates 6.668° S, 111.379° E in the waters of Rembang from October 14 to 17, 2023. The ADCP measured wave parameters at 10-minute intervals, which were then averaged to obtain hourly time series data.

WW3 is one of the numerical models that has been used in operational wave prediction in the world, including Indonesia (Alves *et al*., 2023; Kazeminezhad & Ghavanini, 2023; Kurniawan *et al*., 2021; Rogers *et al*., 2014; Valiente *et al*., 2023; Zieger *et al*., 2019). The model uses bathymetry and wind data to obtain realistic wave parameters. Previous studies have demonstrated the reliability of WW3 in reproducing wave parameters (Amarouche *et al*., 2023; Kessali *et al*., 2023; Umesh & Behera, 2020). WW3 solves the action density balance equation as expressed in the following equations.

$$\frac{\partial N}{\partial t} + \frac{1}{cos\phi\ \partial\phi}\dot{\phi}N\ cos\theta + \frac{\partial}{\partial\lambda}\dot{\lambda N} + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial\theta}\dot{\theta_g}N = \frac{S}{\sigma}$$

where t, λ, φ, θ, k, and σ are the time, longitude, latitude, wave direction, wave number, and intrinsic angular frequency, respectively. The left-hand side of the equation expresses the rate of local change of wave action density, propagation in space, action density shifting, and direction. The net source term (S) on the right-hand side of the equation represents all effects of generation and dissipation, which can be defined as:

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{db} + S_{tr} + S_{sc} + S_{ice} + S_{ref} + S_{xx}$$

In deep water, the source term consists of wind-wave interaction (S_{in}), non-linear wave-wave interaction (S_{nl}), and dissipation by white-capping (S_{ds}). Meanwhile, in shallow water, the source term generally includes wave-bottom interactions (S_{bot}), depth-induced breaking (S_{db}), and triad wave-wave interactions (S_{tr}). WW3 also provides other source terms, including scattering of waves by bottom features (S_{sc}), wave-ice interactions (S_{ice}), reflection off shorelines or floating objects such as icebergs (S_{ref}), and user-defined source terms (S_{xx})(WW3DG, 2016).

The WW3 model data used in this study was obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) over a period of 10 years, from 2014 to 2023. The WW3 model has been used operationally by BMKG since 2014. The model is forced by 10-meter height wind data from the Global Forecasting System (GFS) model, with a spatial resolution of 0.0625° (approximately 7 km), and a temporal resolution of 3 hours (Kurniawan *et al*., 2021).

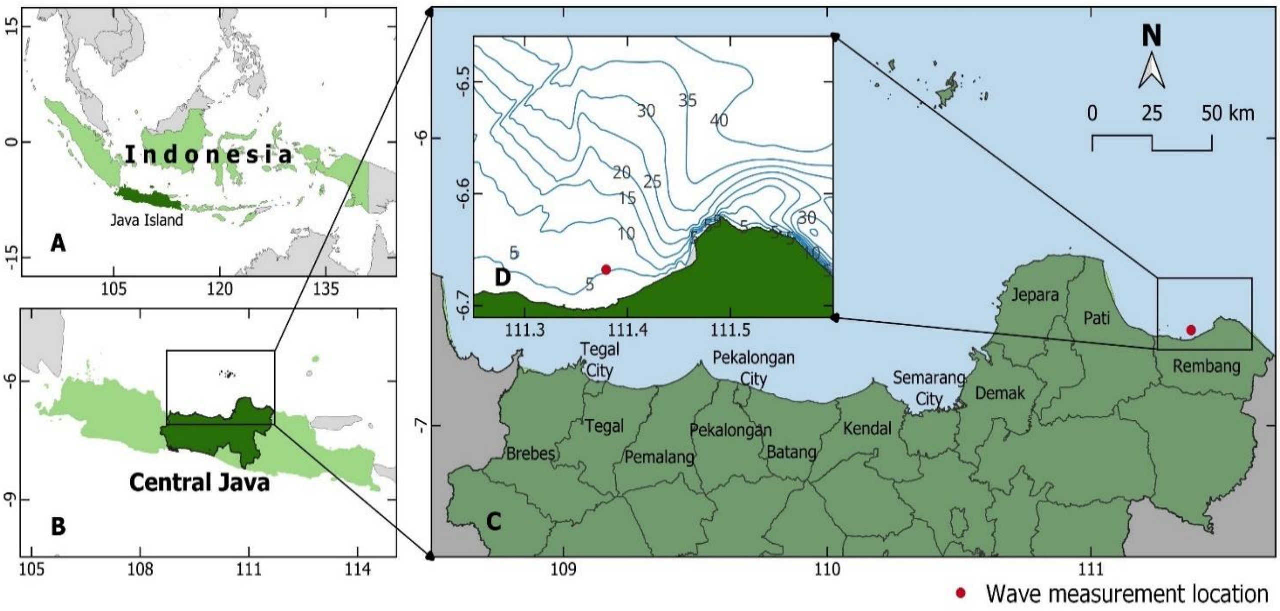

Figure 1. The study area is described in a sequence: (A) Indonesian border (light green) with Java Island depicted in dark green, (B) Java Island (light green) and Central Java (represented as dark green), (C) Northern Waters of Central Java as the Area of Interest, (D) Bathymetric contour around the wave measurement location.

The significant wave height (Hs) data from the WW3 model was verified against the measurement data from October 14 to 17, 2023. Verification was conducted at hourly data intervals, so the WW3 data needed to be linearly interpolated to obtain hourly time series data. The verification process was carried out using statistical parameters, including Pearson correlation coefficient (R), Root Mean Square Error (RMSE), and bias, as expressed in the following equations. The Pearson correlation coefficient is used to determine the strength of the relationship between model data and measurement data. RMSE is a variable used to determine the magnitude of the deviation between the model output and the measurement data. Meanwhile, bias is the difference between the average model output and the average measurement data (Wilks, 2006).

$$\mathrm{R} = \frac{\sum X_{Mi}X_{oi} - \frac{1}{N}\sum X_{Mi}\sum X_{oi}}{\sqrt{\left[\sum {X_{Mi}}^2 - \frac{1}{N}(\sum X_{Mi})^2\right]}\left[\sum {X_{oi}}^2 - \frac{1}{N}(\sum X_{oi})^2\right]}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{Mi} - X_{oi})^2}$$

$$Bias = \frac{1}{N}\sum_{i=1}^{N}(X_{Mi} - X_{oi})$$

With X_{Mi} and X_{oi} each indicating the i^{th} data from the model output and measured data, N indicates the amount of data.

We analyzed the monthly averaged wave height and wave direction characteristics in the northern waters of Central Java from 2014 to 2023. The average value is generally used to analyze seasonal wave variability (Fan, 2024; Galanis et al., 2012; Lv et al., 2014; Ningsih et al., 2023; Rizal & Ningsih, 2022). The average value summarizes a large data set into a single value, making it easy to compare with values from other months (Bluman, 2009; Peck et al., 2020). In the case of mean wave direction, the average wave vector calculation is performed. This process consists of three stages: (1) wave direction was decomposed into zonal and meridional components; (2) average values of each component were calculated; and (3) mean wave direction was reconstructed using an Arctangent 2 function (Dodet et al., 2010; Young, 1999).

RESULTS AND DISCUSSION

In general, the WW3 significant wave height shows good agreement with the measurement data, with a correlation coefficient value of 0.79 (Figure 2). The significant wave height shows lower values than the measurement data (underestimate), as indicated by a negative bias value and an RMSE of 0.2 m. These results show that the WW3 model generally represents actual wave patterns well, although the actual wave height may be higher than the WW3 estimates. This underestimation is possibly due to fair weather conditions during the wave measurements, as indicated by previous studies (Kalourazi et al., 2021; Mentaschi et al., 2015).

The monthly average wave height from January to April in the northern waters of Central Java can be seen in Figure 3. From January to February, wave heights range from 0.2 m to 1.0 m, with wave directions generally from the west-northwest. In March, wave heights gradually decrease to a range of 0.2 m to 0.4 m. Wave heights continue to decrease, reaching a minimum in April with values between 0.2 m - 0.4 m. In April, wave directions begin to shift to the north-northeast.

Figure 4 shows the average wave height from May to August. In May and June, wave heights increase, ranging from 0.2 m to 0.8 m. During these months, wave directions are generally from the north-east. Wave heights further increase in June, ranging from 0.2 m to 1.0 m, and reaching a maximum in August with wave heights ranging from 0.2 m to 1.2 m.

The monthly average wave height of September, October, November, and December is represented in Figure 5. In September, wave heights range from 0.2 m to 1.0 m with directions from the north-east, showing a decrease from the wave heights in August. In October, wave heights range from 0.2 m to 0.6 m with directions similar to those in September. Wave heights continue to decrease in November, ranging from 0.2 m to 0.4 m, with wave directions generally from the north-east. In December, wave heights are observed to increase again, ranging from 0.2 m to 0.6 m. During this month, wave directions shift to the northwest.

Wave height in the northern waters of Central Java tends to be higher in December, January, February, as well as in July, August, and September. The December-January-February (DJF) period is the active phase of the Asian monsoon, causing winds to blow from the Asian continent towards Australia, passing through Indonesia. Meanwhile, the June-July-August (JJA) period is the active phase of the Australian monsoon, causing winds to blow from the Australian continent towards Asia, passing through Indonesia. High waves in Indonesian waters generally occur during these months (Kurniawan *et al*., 2011; Purwanto *et al*., 2021). The significant wave height reached its peak value in August. This finding indicates that the significant wave height during the Australian Monsoon period is higher than during the Asian Monsoon, which aligns with previous studies (Efendi *et al*., 2023; Nugroho *et al*., 2022; Rachmayani *et al*., 2018).

Meanwhile, wave conditions in the northern waters of Central Java tend to be lower in March, April, May, June, October, and November. Wind speeds along the northern coast of Java during the March-April-May (MAM) and September-October-November (SON) periods are lower compared to wind speeds during the DJF and JJA periods (Ma'rufatin *et al*., 2024). The lower wind speeds during these periods contribute to relatively lower wave conditions compared to other months (Purwanto et al., 2021).

The wave direction is influenced by the seasonal variability of wind direction during each monsoon period (Sprintall *et al*., 2014). This wave direction variability affects wave height variability since some areas are sheltered by coastline features. During December to March, wave directions generally come from the west-northwest, resulting in relatively lower wave heights in areas with coastlines facing east, such as the coasts of Pati and parts of Rembang. Conversely, during July to September, wave directions generally come from the northeast, resulting in relatively lower wave heights for the coasts of Semarang, Demak, and parts of Jepara.

The insights obtained from this study are crucial for several aspects of maritime activity planning. For marine transportation, knowing that wave heights are higher in December, January, February, July, August, and September can assist in planning voyages during periods of lower wave activity. Port authorities can anticipate high waves during the active monsoon phase to ensure the safety of port operations. Additionally, understanding wave characteristics aids in designing and maintaining port infrastructure to withstand wave impact.

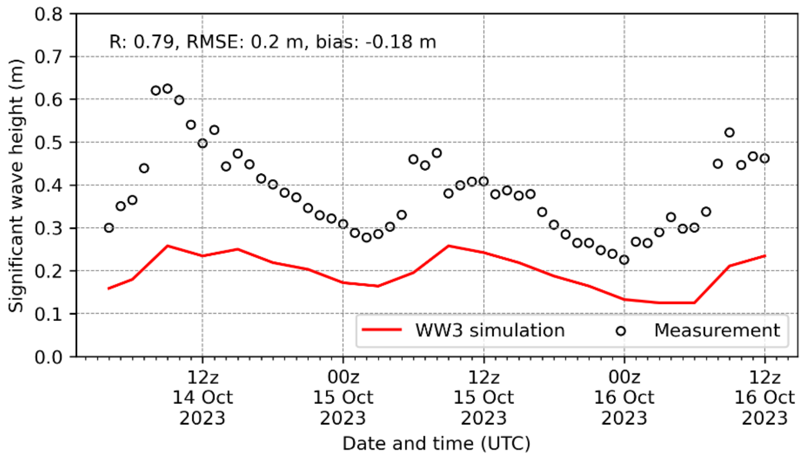

Figure 2. Comparison of significant wave height (m) between WW3 simulation and measured data.

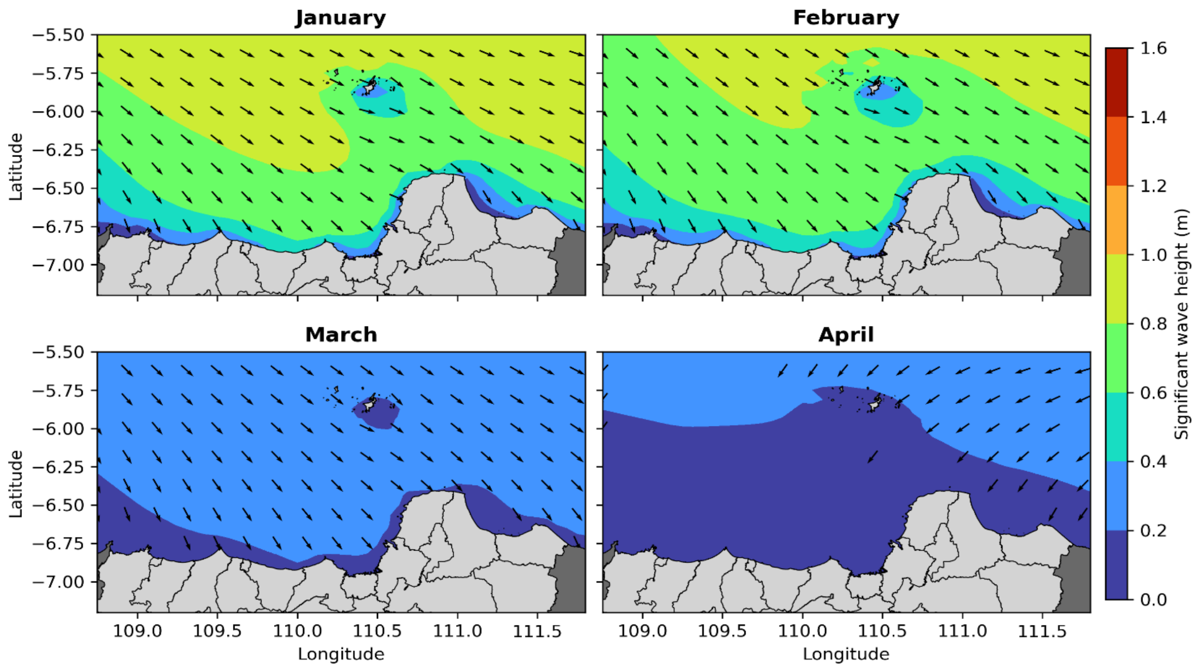

Figure 3. Average significant wave heights in January, February, March, and April 2014 - 2023.

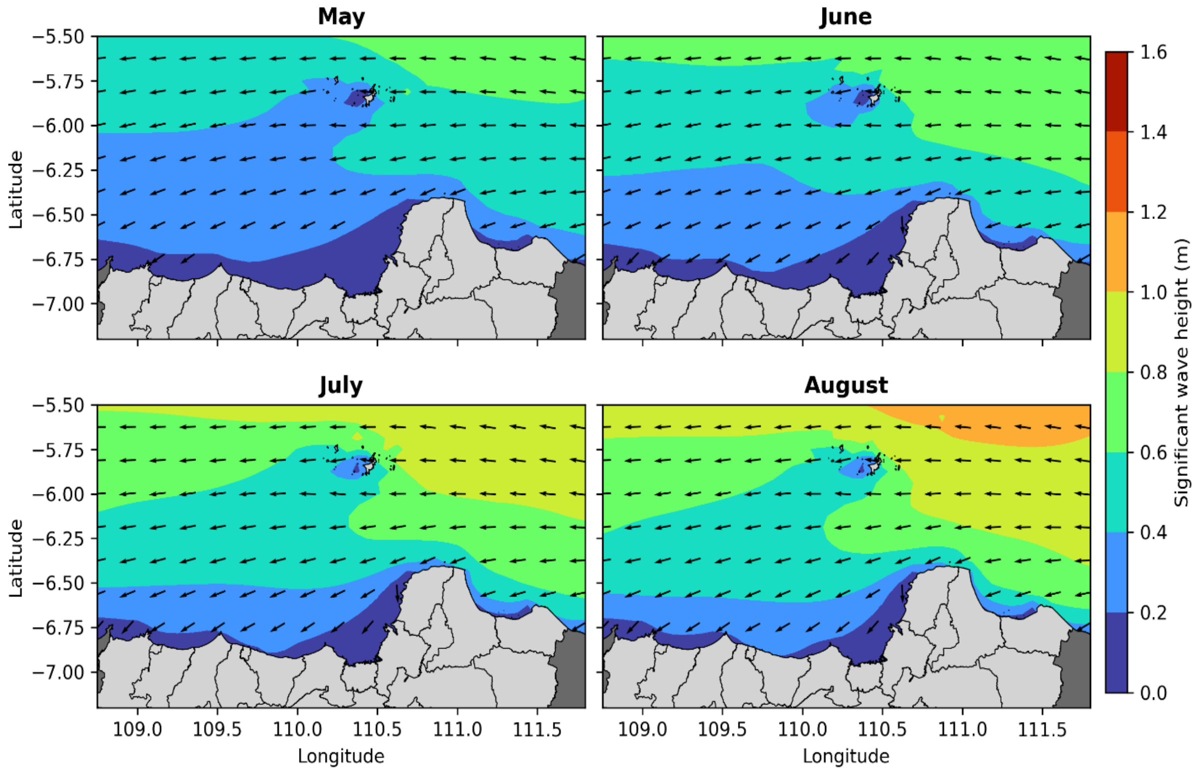

Figure 4. Average significant wave heights in May, June, July, and August 2014 – 2023

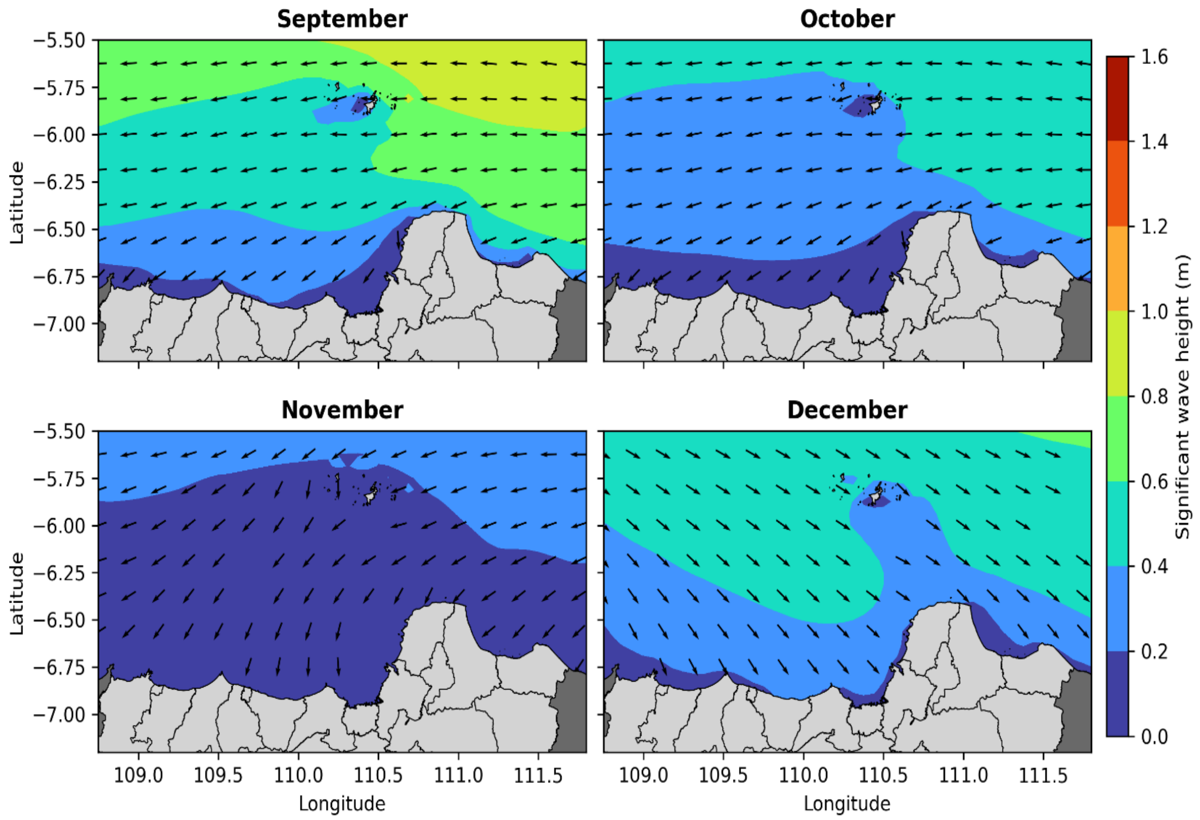

Figure 5. Average significant wave heights in September, October, November, and December 2014 - 2023

CONCLUSION

This study characterizes significant wave height and wave direction in the Northern Waters of Central Java. Using wave hindcast datasets from the WW3 numerical model for the period from 2014 to 2023, the research provides detailed insights into wave characteristics. The WW3 model generally represents actual wave patterns well, though it tends to underestimate actual wave heights. Wave height in the northern waters of Central Java tends to be higher in December, January, February, July, August, and September, ranging from 0.2 m to 1.2 m. Meanwhile, wave height tends to be lower in March, April, May, June, October, and November, ranging from 0.2 m to 0.8 m. The wave direction is from the west-northwest in December to March, while the wave direction is from the east-northeast in April to November. The variability of wave direction affects the variability of significant wave height in the area near the coastline as well.

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