IMPACT OF SIGNIFICANT WAVE HEIGHT, WIND SPEED, AND PRECIPITATION VARIABILITY ON SHIPPING SAFETY IN INDONESIAN ARCHIPELAGIC SEA LANES

DAMPAK VARIABILITAS KETINGGIAN GELOMBANG SIGNIFIKAN, KECEPATAN ANGIN DAN CURAH HUJAN TERHADAP KESELAMATAN PELAYARAN DI ALUR LAUT KEPULAUAN INDONESIA

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ABSTRACT: Unexpected and unpredictable extreme weather poses significant risks to maritime activities, particularly in Indonesian waters and the Indonesian Archipelagic Sea Lanes, known as ALKI, which have been internationally recognized for shipping and aviation since 1985. This study assesses these risks by analyzing patterns of wave height, wind speed, and rainfall along ALKI to improve shipping safety and mitigate accident risks. Data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 for the period 1993 to 2023 and Global Precipitation Measurement (GPM) for 2001 to 2020 were processed using descriptive statistics and Empirical Orthogonal Function (EOF) methods. The results reveal high waves (1-2.5 m) and strong winds at Beaufort scale 4 prevailing in northern Indonesian waters from December to February and southern waters from June to August. Higher rainfall (350-600 mm) occurs in the northern region from September to November and in the southern from December to February. Extreme waves (90th percentile) reach up to 3 m in open ocean areas such as the Natuna Sea, western Sumatra, southern Java, the Maluku Sea, and northern Papua Sea. Extreme winds are observed over open ocean areas, with slight spatial shifts, as seen in the Arafura Sea (9-10 m/s). Extreme rainfall (250-350 mm) is concentrated in the northwestern region. EOF analysis identifies global climate phenomena and regional oceanographic dynamics as the primary drivers of significant wave height variability. Improved understanding of weather variability can enhance navigation safety along the ALKI routes and inform more effective regulation, law enforcement, and monitoring.

Keywords: Indonesian archipelagic sea lanes, significant wave height, wind speed, rainfall, shipping safety

***ABSTRAK**: Cuaca ekstrem yang tidak terduga dan tidak terprediksi berisiko besar terhadap aktivitas maritim, terutama di perairan Indonesia dan Alur Laut Kepulauan Indonesia (ALKI) yang telah diakui secara internasional untuk pelayaran dan penerbangan sejak 1985. Penelitian ini dilakukan untuk memahami penyebab risiko tersebut dengan mengkaji pola tinggi gelombang, kecepatan angin, dan curah hujan di ALKI dalam rangka meningkatkan keselamatan pelayaran dan mengurangi kecelakaan. Analisis dilakukan dengan menggunakan statistik deskriptif dan Empirical Orthogonal Function (EOF) terhadap data European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 periode 1993-2023 dan data Global Precipitation Measurement (GPM) tahun 2001-2020. Hasil analisis menunjukkan gelombang tinggi (1–2,5 m)* *dan angin kencang pada skala Beaufort 4 dominan di perairan utara Indonesia pada Desember hingga Februari dan perairan selatan pada Juni hingga Agustus. Curah hujan yang lebih tinggi (350–600 mm) terjadi di wilayah utara pada September hingga November dan di wilayah selatan pada Desember hingga Februari. Gelombang ekstrem (persentil ke-90) dapat mencapai hingga 3 m di perairan laut lepas seperti Laut Natuna, barat Sumatra, selatan Jawa, Laut Maluku, dan Laut Papua bagian utara. Angin ekstrem teramati di area laut lepas dengan sedikit pergeseran spasial, seperti di Laut Arafura (9–10 m/detik). Curah hujan ekstrem (250–350 mm) terkonsentrasi di wilayah barat laut. Analisis EOF mengidentifikasi fenomena iklim global dan dinamika oseanografi regional sebagai faktor utama yang memengaruhi variabilitas tinggi gelombang signifikan. Pemahaman yang lebih baik tentang variabilitas cuaca dapat meningkatkan keselamatan navigasi di sepanjang jalur ALKI serta mendukung regulasi, penegakan hukum, dan pengawasan yang lebih efektif.*

Kata Kunci: *Alur Laut Kepulauan Indonesia, tinggi gelombang signifikan, kecepatan angin, curah hujan, keselamatan pelayaran*

INTRODUCTION

Indonesia is an archipelagic country with an extensive maritime area. Its strategic geographic location between two continents and two oceans brings significant political, economic, and security value to Indonesia and is also recognized by other countries (Hutagalung, 2017). This position allows Indonesia's maritime territory to function as an international shipping corridor. To regulate this, the Indonesian government enacted Law No. 17 of 1985, which ratified the United Nations Convention on the Law of the Sea (UNCLOS) of 1982 and established a consensus dividing Indonesia's waters into three designated routes known as the Indonesian Archipelagic Sea Lanes (ALKI). The ALKI routes are highly strategic for Indonesia, as international vessels and aircraft can pass through them continuously and efficiently without obstruction (Batara, 2023; Napitupulu et al., 2022a). This creates both opportunities and responsibilities for the national economy to grow in areas such as shipping, navigation, marine industries, and trade (Nainggolan, 2016; Prasetyo et al., 2020).

According to Law No. 31 of 2021 on the Implementation of Shipping, shipping is defined as an integrated system of water transportation, port operations, safety and security, and marine environmental protection. Indonesian-flagged vessels permitted to operate internationally include passenger ships, cargo ships with a gross tonnage of 500 GT or more, and mobile offshore drilling units. In addition, the law also regulates the types and functions of ships that may be used in both national and international shipping (Apriyanto et al., 2019). Ship categories authorized for operation include passenger ships, cargo ships, mobile offshore drilling units, fishing vessels, research vessels, and naval ships (Monika et al., 2022; Xing & Zhu, 2021).

The shipping and marine industries represent a potential strength for Indonesia's development as a maritime nation (Batara, 2023; Prasetyo et al., 2020). However, one aspect that needs to be cautious considered in shipping is extreme and unpredictable weather conditions. Such conditions can endanger crew and passenger safety, damage ships and even cause casualties. The International Convention for the Safety of Life at Sea (SOLAS) serves as the main regulation of international shipping safety, including provisions for dealing with extreme weather and planning safe routes. SOLAS provides guidance for national regulations, institutions, and shipping companies to collectively ensure maritime safety. In Indonesia, coordination among agencies such as the Meteorology, Climatology and Geophysics Agency (BMKG) and port authorities is essential for providing accurate and timely information, including weather observation, early warning, shipping routes, and vessel positioning. Furthermore, Law No. 17 of 2008 on shipping and the Minister of Transportation Regulation No. 20 of 2015 on shipping safety standards require shipping companies to plan safe routes by considering weather conditions, sea traffic, and accident-prone areas. According to the National Search and Rescue Agency (*Badan Nasional Pencarian dan Pertolongan*, BASARNAS) statistics for 2022, there were 823 reported maritime accidents resulting in injuries, fatalities, and missing persons, affecting a total of 6510 individuals. Based on investigations by the National Transportation Safety Committee (*Komisi Nasional Keselamatan Transportasi*, KNKT), these accidents were caused by various factors, including fires, engine explosions, collisions, listing and sinking of vessels, and capsizing. Among these, adverse weather conditions remain a significant contributing factor.

Based on accident reports published by the KNKT, several severe maritime incidents have been documented and analyzed. The first involved the cargo vessel Multi Prima I, which sank on November 22, 2018, in the Kapoposang Bali–Mataram waters, East Nusa Tenggara. The report noted wind speeds of 5–8 m/s and wave heights reaching 4 m at the time of the incident. Similar wind conditions were observed in January in the Flores Sea, when another cargo vessel, Itanini, capsized due to extreme winds and waves estimated at 2.5–3 m in height. On December 29, 2016, the passenger ship Karamando sank south of Jailolo Port, North Maluku, amid high waves ranging from 4–5 m. Another incident involved MV Marina Bari 2B, which rolled over and sank after being struck by 5 m waves; BMKG reported wind speeds there reaching up to 23 m/s. Most of these incidents were also accompanied by light to heavy rainfall.

Weather and climate phenomena can change significantly at any time due to various factors, such as storms, tropical cyclones, earthquakes, tsunamis, and global warming, which contributes to climate change and sea level rise (Akbar et al., 2024; Napitupulu, 2025; Nurdjaman et al., 2023). These changes can disrupt typical weather patterns in specific regions and may negatively affect certain communities and human activities (Nagi et al., 2023; Ningsih et al., 2023). Climate change, in particular, can have adverse impacts on maritime transport by altering shipping routes, increasing hazards and the risk of damage to maritime infrastructure, reducing the efficiency of transport operations, and raising the frequency of maritime accidents (Izaguirre et al., 2021; Monios & Wilmsmeier, 2020; Napitupulu et al., 2025).

The wind patterns over Indonesia are primarily influenced by the monsoon cycle (Bayong Tjasyono et al., 2008; Napitupulu, 2024). This cycle is driven by the apparent position of the sun relative to the Earth's latitude. Generally, from June to August, the tilt of the Earth results in greater solar exposure over the northern hemisphere, corresponding to summer conditions (Napitupulu et al., 2022b). Meanwhile, it is winter in the southern hemisphere. During this period, winds predominantly blow from the southern hemisphere (characterized by colder temperatures and higher pressure) toward the northern hemisphere (warmer, lower pressure). This phase is referred to as the Australian Monsoon in Indonesia, as the prevailing winds originate from Australia. In contrast, from December to February, the apparent position of the sun shifts toward the southern hemisphere, resulting in summer there and winter in the northern hemisphere (Napitupulu et al., 2022c). Consequently, winds primarily blow from Asia (cold, high pressure) toward Australia (warm, low pressure), a phase known as the Asian Monsoon.

Waves are primarily generated by wind forcing (Kara, 2016; Radjawane et al., 2023). This process disturbs the water's surface tension, resulting in variations in water level. Wave conditions can differ considerably depending on the prevailing wind systems (Ningsih et al., 2023). Interactions between the atmosphere and ocean, particularly between wind and waves, directly influence maritime activities such as fisheries, shipping, marine research, and transportation.

The Indonesian region is characterized by strong convective activity, which leads to highly variable rainfall patterns. Indonesian waters serve as one of the world's most significant convection centers, playing a critical role in the climate system of the equatorial region and acting as an indicator of shifts in climate variability (Yamanaka et al., 2018). Rainfall variability in Indonesia is influenced by several factors, including the Asia–Australia monsoon, the Intertropical Convergence Zone (ITCZ), the El Nino–Southern Oscillation (ENSO), and topographic effects. Indonesian rainfall patterns are generally classified into three types: monsoonal, equatorial, and local patterns (Aldrian & Susanto, 2003).

The monsoonal pattern features peak rainfall during December, January, and February (DJF). Regions that exhibit this pattern include southern Sumatra, central and southern Kalimantan, Java, Bali, Nusa Tenggara, and parts of Papua. The equatorial pattern is characterized by two rainfall peaks, typically around March and September during the equinoxes, and is generally observed in northern Sumatra and northern Kalimantan. In contrast, the local pattern shows peak rainfall during June, July, and August (JJA), which is opposite to the monsoonal pattern. This local pattern is typically found in Maluku, Sulawesi, and parts of Papua. Accordingly, this study aims to analyze weather patterns, including wind, wave, and rainfall variability, along ALKI-I, ALKI-II, and ALKI-III to inform safer shipping schedule planning.

METHODS

Three routes of the Indonesian Archipelagic Sea Lanes (Alur Laut Kepulauan Indonesia, ALKI) were selected as the areas of interest (Figure 1). From north to south, these comprise ALKI-I, ALKI-II, and ALKI-III. ALKI-I includes the Malacca Strait, Natuna Sea, Karimata Strait, Java Sea, and Sunda Strait. ALKI-II covers the Celebes Sea, Makassar Strait, Flores Sea, and Lombok Strait. ALKI-III encompasses the Maluku Sea, Seram Sea, and Banda Sea, and is divided into three sub-routes: (1) ALKI-III A, from the Banda Sea through the Ombai Strait into the Sawu Sea and exiting to the Indian Ocean; (2) ALKI-III B, from the Banda Sea through the Leti Strait into the Timor Sea; and (3) ALKI-III C, extending eastward from the Banda Sea to the Arafura Sea.

This study used secondary data consisting of significant wave height (combined wind waves and swell) and 10 m u-component and v-component wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset, with 6-hourly intervals. The ERA5 dataset covers 30 years (1993–2023) for the Indonesian region, spanning 7.5° N to 13.0° S in latitude and 96.0° E to 134.5° E in longitude. In addition, daily rainfall data were obtained from the Global Precipitation Measurement (GPM) dataset, covering 20 years (2001–2020) and spanning 15.0° S to 10.0° N in latitude and 90.0° E to 149.0° E in longitude.

The significant wave height parameter represents the average height of the highest one-third of surface ocean or sea waves generated by wind and swell (Yamanaka et al., 2018). It measures the vertical distance between the wave crest and trough (Napitupulu et al., 2021). The ocean surface wave field consists of a combination of waves with different heights, wavelengths, and directions, known as the two-dimensional wave spectrum (Suprijo et al., 2024). This spectrum can be decomposed into wind-sea waves, which are directly driven by local winds, and swell, which consists of waves generated by winds at distant locations and times (Radjawane et al., 2024). Significant wave height is commonly used to describe sea state and swell conditions. For example, engineers use this parameter to estimate loads on offshore structures,

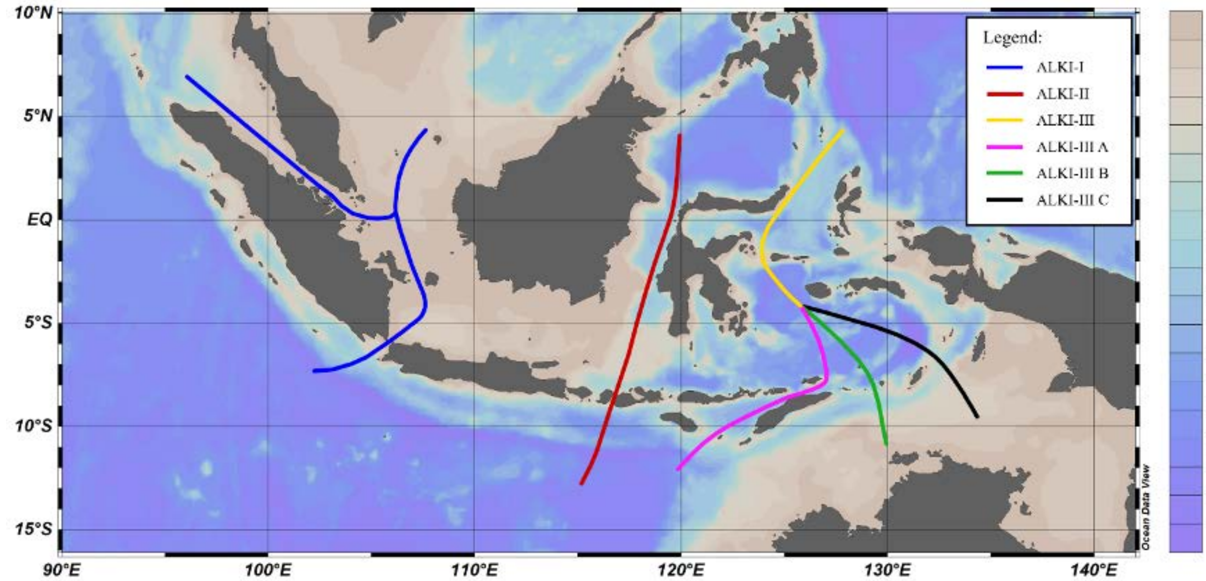

Figure 1. Indonesian Archipelago Sea Lanes (ALKI) routes.

Table 1. Classification of wave height categories in Indonesian waters (BMKG, 2024).

No	Description	Wave height range (m)
1	Calm	0.10 – 0.50
2	Low	0.50 – 1.25
3	Moderate	1.25 – 2.50
4	High	2.50 – 4.00
5	Very High	4.00 – 6.00
6	Extreme	6.00 – 9.00
7	Very Extreme	9.00 – 14.00

Table 2. Beaufort scale classification (Royal Meteorological Society, 2024).
*) These values refer to the well-developed wind waves of the open sea

Beaufort wind scale	Wind descriptive terms	Limits of wind speed (m/s)	Sea state	Sea descriptive terms	Probable wave height (m)*
0	Calm	<1	0	Calm (glassy)	-
1	Light air	1-2	1	Calm (rippled)	0.1
2	Light breeze	2-3	2	Smooth (wavelets)	0.2
3	Gentle breeze	4-5	3	Slight	0.6
4	Moderate breeze	6-8	3-4	Slight – Moderate	1.0
5	Fresh breeze	9-11	4	Moderate	2.0
6	Strong breeze	11-14	5	Rough	3.0
7	Near gale	14-17	5-6	Rough – Very rough	4.0
8	Gale	17-21	6-7	Very rough – High	5.5
9	Strong gale	21-24	7	High	7.0
10	Storm	25-28	8	Very High	9.0
11	Violent storm	29-32	8	Very High	11.5
12	Hurricane	>33	9	Phenomenal	>14

Table 3. Rainfall intensity classification (BMKG, 2024)

No	Description	Rainfall intensity (mm/day)
1	Cloudy	0 – 0.5
2	Light rain	0.6 - 20
3	Moderate rain	21 - 50
4	Heavy rain	51 - 100
5	Very heavy rain	101 - 150
6	Extreme	> 150

such as oil platforms, or for coastal engineering applications (Abdullah et al., 2022).

According to the National Agency of Meteorology, Climatology, and Geophysics (BMKG), wave height classifications are shown in Table 1. The Beaufort scale (Table 2) is also used, as it provides a standard basis for estimating wind force at sea (Kara, 2016). As illustrated by the cases described earlier, extreme waves in Indonesian waters can be categorized as high (2.5–4 m) or very high (4–6 m), excluding tsunami events. Wind conditions in these events typically reached the 4th to 5th level on the Beaufort scale, while in one extreme case, gale-force winds corresponding to level 8 were observed. In addition, rainfall intensity classifications defined by BMKG are presented in Table 3.

The collected data were first summarized using descriptive statistics and compositely visualized in monthly averaged spatial maps. The 90th percentile was then calculated to identify extreme values of wave height, wind speed, and rainfall, enabling the identification of potential extreme events within the dataset. Furthermore, Empirical Orthogonal Function (EOF) analysis was applied to examine the climate patterns influencing wave height variability along each ALKI route. Each mode derived from the EOF represents an independent spatial pattern (eigenvector), and its associated variance is quantified by an eigenvalue. This analysis helps to identify the dominant modes driving wave height variability in the study area.

RESULTS AND DISCUSSIONS

Monthly Variations of Significant Wave Height, Sea Surface Wind, and Precipitation

Figure 2 shows the monthly distribution of significant wave heights (Hs) across Indonesian waters. Overall, the seas inside the archipelago tend to be relatively calmer compared to offshore areas. In the northern part of ALKI-I, particularly the Natuna Sea, moderate waves ranging from 1.5 to 2.5 m are observed between November and February, driven by swells propagating from the South China Sea. Wave heights typically peak in December and January, reaching up to 2.5 m. At the mouth of the Malacca Strait, wave conditions are influenced by the Indian Ocean. Higher waves generally occur from April to October, coinciding with the Australian Monsoon, when winds form cyclonic patterns along the western coast of Sumatra (Kartadikaria et al., 2024). The peak of the Australian Monsoon, between June and August, results in significant wave heights of around 1–2 m. In contrast, the inner Malacca Strait remains considerably calmer because wave propagation is limited by Sumatra and western Malaysia. A similar low-wave pattern appears in the Karimata Strait, although slightly higher due to exposure to swells from the Natuna Sea and South China Sea, with waves reaching 1–1.5 m during December to February. In the Java Sea, waves propagate in January with heights around 1 m. Further south, towards the Sunda Strait, the waters open to the Indian Ocean. During the Asian Monsoon (November to March), wave heights reach around 2 m, while in the Australian Monsoon period, waves can exceed 3 m. These findings are consistent with previous studies. Wicaksana et al. (2015) and Anggara et al. (2018) reported that significant wave heights in the Natuna Sea, Karimata Strait, and Java Sea during the Asian and Australian Monsoons typically range between 0.3–3.3 m, 1–3 m, and 0.5–2.5 m, respectively. Furthermore, extreme events can produce wave heights exceeding 3 m, and in rare cases, waves in the Natuna Sea may reach up to 5.1 m during the winter season (Anggara et al., 2018; Muliati et al., 2019).

In ALKI-II, the route is more straightforward compared to the other lanes, beginning in the Celebes Sea, which has limited exposure to the Pacific Ocean.

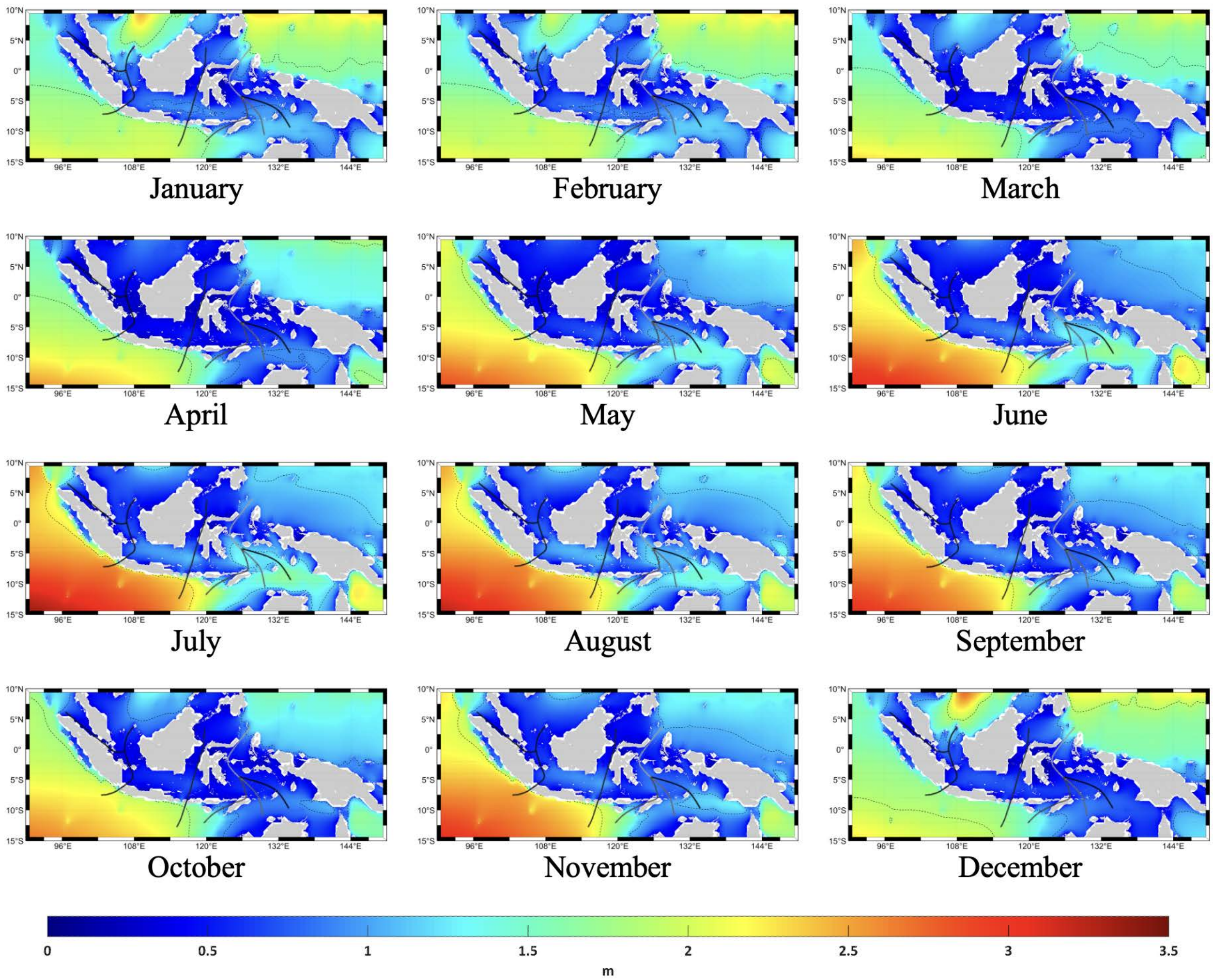

Figure 2. Monthly average significant wave height (SWH) from January 1993 to December 2023. The dashed line indicates the 2 m SWH contour.

Waves in this section generally remain low from November to March and tend to peak slightly in January and February, reaching just over 1 m. In the Makassar Strait, wave heights rarely exceed 1 m. Similar characteristics were reported by Labania et al. (2021), who found that maximum wave heights in the Makassar Strait typically range from 0.5 to 0.9 m. Further south, the Flores Sea is more open, allowing waves to build up to around 1–1.5 m in July and August. Higher waves occur outside the southern entrance of the Lombok Strait, which directly faces the Indian Ocean. As in the Sunda Strait, wave heights here can reach around 2 m during the Asian Monsoon and exceed 3 m during the Australian Monsoon, particularly between June and August.

ALKI-III begins in the Pacific Ocean, which is characterized by moderate wave activity during the Asian Monsoon period. Wave heights exceeding 2 m are observed from December to March, although these waves tend to dissipate slightly in the Maluku Sea, where they range between 1–2 m. Lail et al. (2018) similarly reported wave heights of around 1–1.5 m during the western season in Sangihe District, near the Maluku Sea. The Seram Sea, being more enclosed, generally experiences calm conditions throughout the year. In contrast, the Banda Sea is affected by the Australian Monsoon from May to August, with wave heights reaching approximately 1–1.5 m. Beyond this point, ALKI-III splits into three passages: ALKI-III A, B, and C. ALKI-III A passes through the Ombai Strait before reaching the southwest of the Sawu Sea. While the Ombai Strait remains relatively calm, the Sawu Sea experiences waves exceeding 1 m year-round, which increase to around 1.5–2 m beyond the Sawu Sea. Along the ALKI-III B route, covering the Leti Strait and the Timor Sea, wave heights exceed 1 m during January and February and become higher during the Australian Monsoon (May to August), with

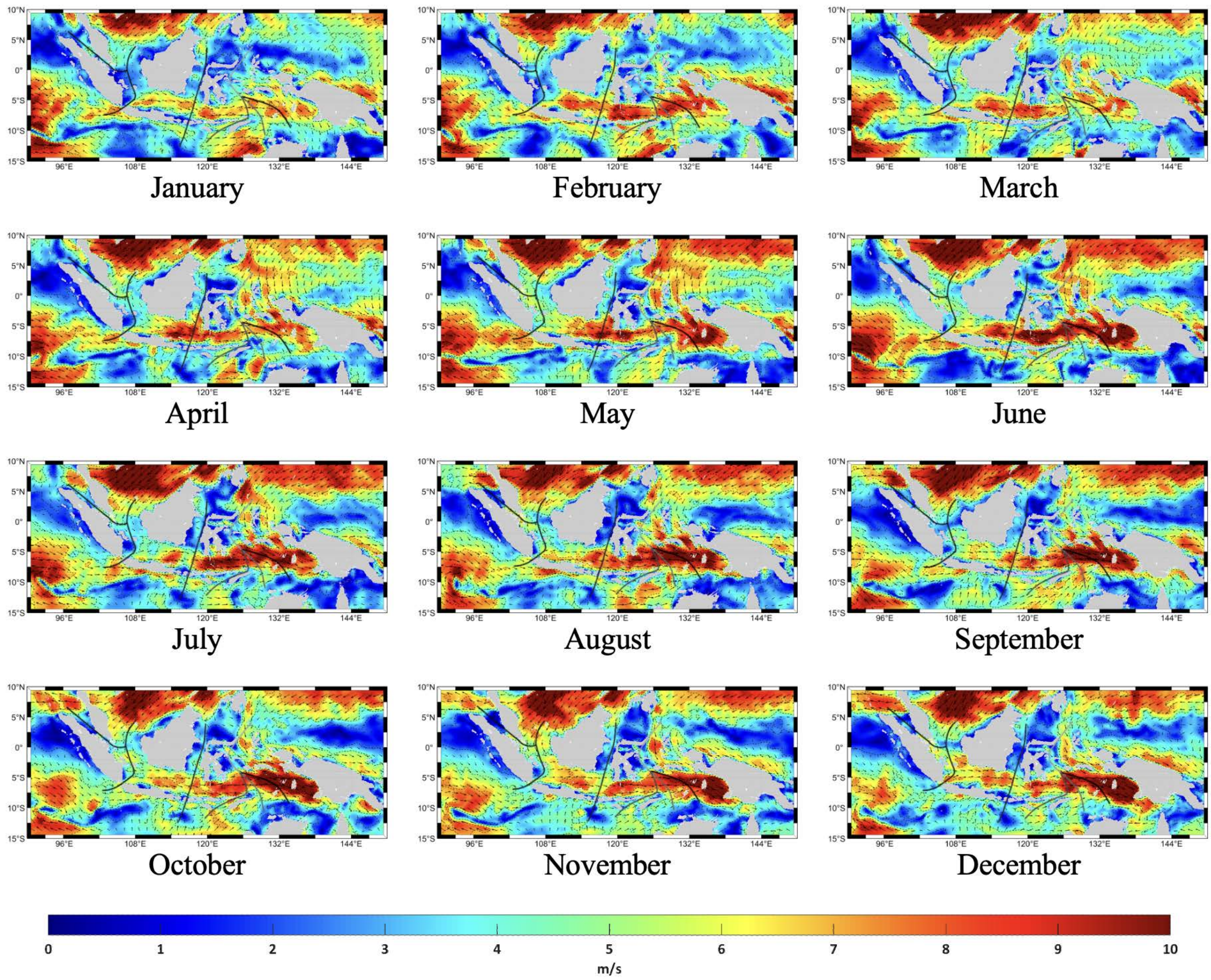

Figure 3. Monthly average 10 m wind speed from January 1993 to December 2023. Dashed line and arrows indicate wind speeds of 5 m/s and prevailing SSW direction.

significant wave heights around 1–1.5 m. A similar seasonal pattern is observed in ALKI-III C, which crosses the Arafura Sea. Here, wave heights reach slightly higher magnitudes and persist for a longer duration, lasting until September.

The wind patterns and their monthly variability are shown in Figure 3. In December, moderate to fresh breezes begin to blow southward from the South China Sea at approximately 8–10 m/s, alongside winds entering from the Pacific Ocean northeast of Indonesia. These winds move into Indonesian waters through several passages, including the Karimata Strait, Makassar Strait, Celebes Sea, and Maluku Sea. By January, wind speeds prevail inside the Java Sea, Flores Sea, and Banda Sea, generally ranging from 5–6 m/s. In the following month, speeds exceed 6 m/s in the Java Sea and rise to over 9 m/s in the Flores Sea, Banda Sea, Timor Sea, and Arafura Sea. Overall, during the Asian Monsoon period, ALKI-I experiences 4th Beaufort scale winds across the Natuna Sea, Karimata Strait, and Java Sea, especially in January and February, reaching up to 7–8 m/s. In ALKI-II, moderate breezes occur in the Makassar Strait, while stronger winds exceeding 8 m/s are observed in the Flores Sea and outside the Lombok Strait, facing the Indian Ocean. Finally, in ALKI-III, 5th Beaufort scale winds prevail along the routes in January, with wind speeds exceeding 9 m/s in February.

During the transition from the Asian monsoon to the Australian monsoon in April and May, moderate breezes begin to blow from Australia, entering from the southeast over the Arafura Sea. These winds can reach up to 8 m/s on the southern side of ALKI-III, covering the Arafura Sea, Timor Sea, Leti Strait, and Banda Sea. As the Australian monsoon sets in by June, moderate winds spread across the Banda Sea and Flores Sea, generally ranging from 7–8 m/s, and extend slightly into the Java Sea and Seram Sea. In this period, winds with speeds of 9–10 m/s are observed in the Arafura Sea, affecting parts of ALKI-II. In July, gentle to moderate breezes prevail across

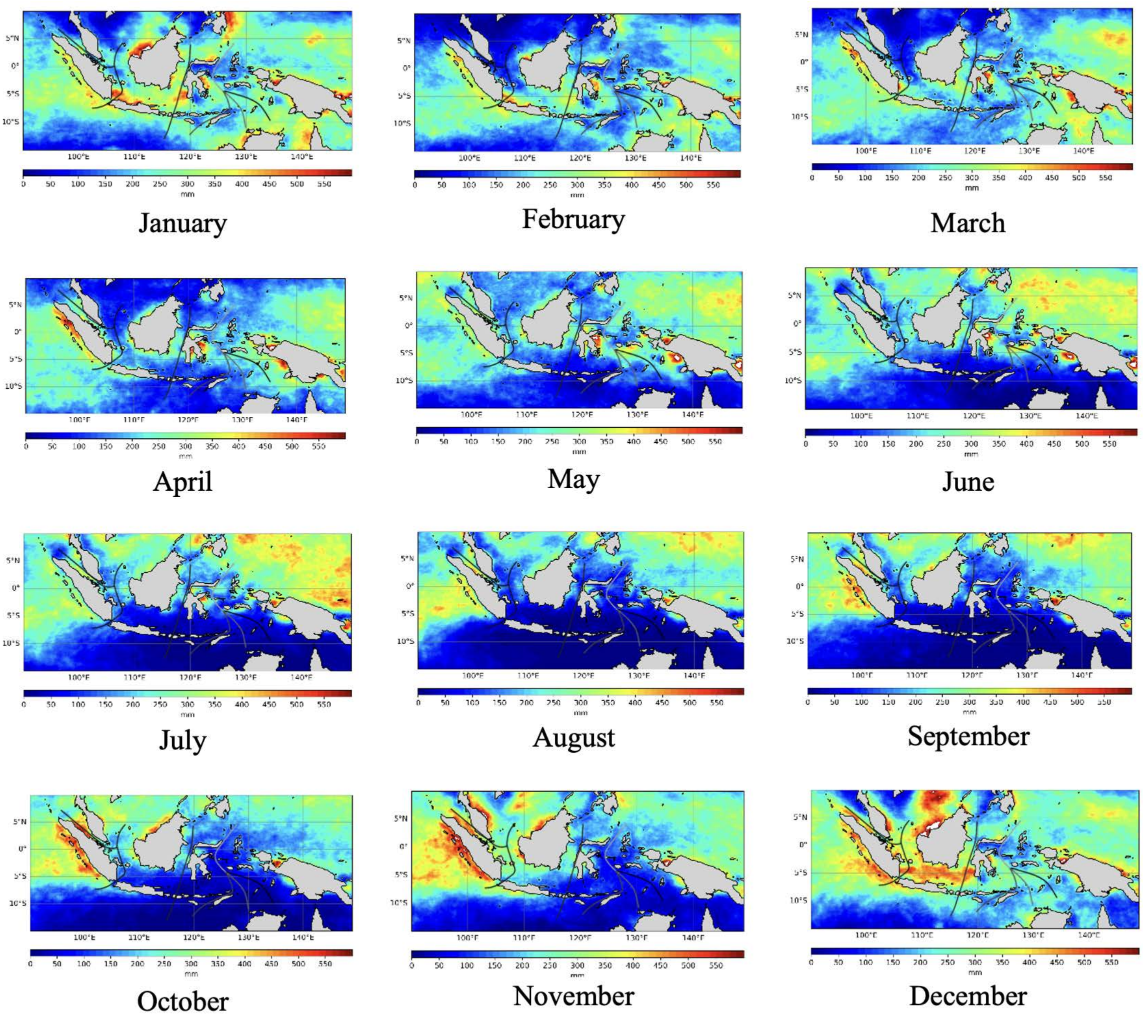

Figure 4. Monthly average precipitation (mm) from January 1993 to December 2023.

the Flores Sea, Java Sea, and Seram Sea, and begin to cross into the Karimata Strait (ALKI-I) at speeds of around 6–7 m/s. The peak season occurs in August, when winds range from 6–7 m/s as they enter the Maluku Sea and blow toward the Pacific Ocean. Stronger winds at the 4th–5th Beaufort scale from the east-southeast also occur over the Flores Sea and southern Java waters, influencing the southern ends of ALKI-I and ALKI-II. These winds continue through September, still prevailing over the Java Sea, Flores Sea, Arafura Sea, and southern Java waters, and remain detectable at the exit of the Sunda Strait into October. The observed patterns are consistent with previous studies by Wicaksana et al. (2015) and Muliati et al. (2018) in the central ALKI-I region, and Lail et al. (2018) in northern ALKI-III.

Figure 4 shows the climatological pattern of rainfall accumulation over Indonesian waters. Overall, rainfall intensity is higher in the southern part of Indonesian waters during DJF (December–February), while the northern part experiences relatively higher intensity during SON (September–November). The climatological rainfall accumulation along ALKI-I generally displays a monsoonal pattern, with peak precipitation during DJF (December–February) ranging from 350–600 mm. This peak is influenced by Asian monsoon winds that transport moist air masses from Asia toward Australia. The northern part of the Malacca Strait records higher rainfall intensity compared to the southern part, likely due to additional rainfall generated by the orographic effect of the Barisan Mountains in northern Sumatra. This finding aligns with Fujita et al. (2010), who noted that the strength of offshore rainfall is determined by the sea's width and surrounding topography. During JJA (June–August), rainfall intensity decreases notably over the Karimata Strait, Java Sea, and Sunda Strait, as the east monsoon winds cross shorter expanses of water, resulting in less humid air masses.

The ALKI-II area exhibited a similar monsoonal rainfall pattern to ALKI-I. The Sulawesi Sea, Makassar Strait, Flores Sea, and Ombai Strait experienced peak rainfall during the Asian monsoon season (DJF) and lower rainfall during the Australian monsoon season (JJA). Rainfall intensity in the JJA period was generally moderate, ranging from 50–100 mm. During DJF, the Makassar Strait recorded higher rainfall intensity, reaching 300–450 mm, while rainfall decreased towards the southern part of ALKI-II waters, particularly in the Ombai Strait, where it ranged around 100–200 mm.

In the ALKI-III region, rainfall variability between the Asian and Australian monsoon periods was notably high. The Banda Sea exhibited a local rainfall pattern, with peak monthly rainfall occurring from May to July, ranging from 200–450 mm. This pattern contrasted with that of the Maluku Sea, where peak rainfall was observed from April to June. The variability in rainfall characteristics across these areas suggests that, in addition to monsoonal influence, local topographic conditions significantly affect convective processes. In ALKI-III C, the Arafura Sea showed a monsoonal rainfall pattern similar to that of ALKI-I and ALKI-II. Rainfall intensity decreased during the transition season (March-April-May, MAM) due to the weakening of Asian monsoon winds that typically carry moist air masses.

Extreme Conditions of Significant Wave Height, Sea Surface Wind, and Precipitation

Figure 5a presents the 90th percentile map of significant wave height, based on 30 years of data. Extreme wave heights reaching approximately 3 m were primarily observed in the open Indian Ocean. In offshore regions surrounding Indonesia, particularly the South China Sea, the Pacific Ocean, western Sumatra, and southern Java waters, extreme waves could reach 2–3 m, which can be classified as moderate to high waves. Extreme wave heights of about 1–2 m were also likely to occur at the mouth of the Malacca Strait, the Natuna Sea, Java Sea, Flores Sea, Maluku Sea, Banda Sea, Arafura Sea, Sawu Sea, and Timor Sea. In contrast, other areas showed relatively calmer conditions, largely due to more sheltered or enclosed topographic features.

As shown in Figure 5b, the spatial pattern of wind speed differs notably from that of significant wave height. Nevertheless, extreme fresh breezes exceeding 10 m/s are observed in the Arafura Sea, as well as in the South China Sea and the Indian Ocean. Moderate to fresh breezes ranging from 8–10 m/s also occur in the Natuna Sea, parts of the Java and Flores Seas, the southern waters off Sumatra and Java, the Banda Sea, the Timor Sea, and south of Bali to the Nusa Tenggara Islands.

Figure 5c shows the climatological extreme rainfall distribution, represented by the 90th percentile from the 20-year dataset. The spatial extent of extreme rainfall is broader than that of average rainfall. Regions close to the equator, particularly around Sumatra and Kalimantan, exhibit higher extreme rainfall, likely driven by tropical air convergence and strong convective processes. In the

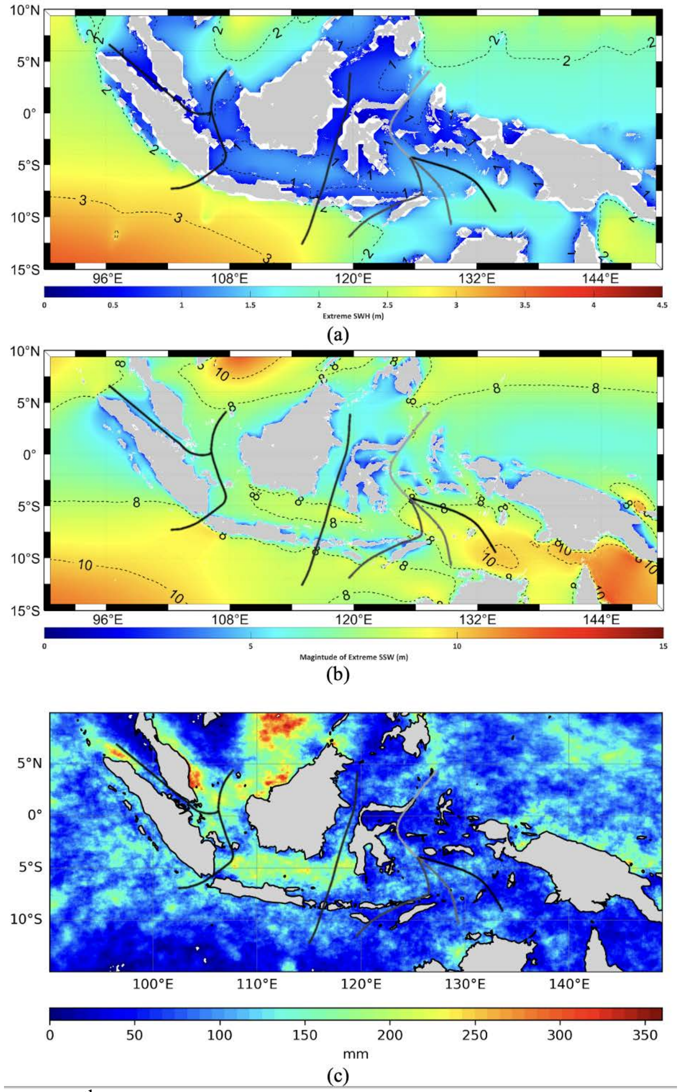

Figure 5. 90th percentile maps of (a) significant wave height, (b) wind speed, and (c) precipitation from January 1993 to December 2023.

Karimata Strait, Java Sea, and Flores Sea, extreme rainfall reaches 150–250 mm. In eastern Indonesian waters, including the Seram Sea, Timor Sea, and Maluku Sea, extreme rainfall is relatively lower, around 50–150 mm. In contrast, western and northern Indonesian waters, particularly the northern Java Sea, Natuna Sea, and South China Sea, record substantially higher extreme rainfall reaching up to 250–350 mm, which is classified by BMKG as very extreme.

Interannual Variability of Significant Wave Height

The Empirical Orthogonal Function (EOF) analysis of SWH data in ALKI-I identified two main patterns of variability, together explaining 79% of the total variance (Figure 6). The first pattern (EOF1) accounts for 44% of the variance and represents the dominant pattern of SWH variability in this region. This mode likely reflects the influence of large-scale climate phenomena, such as the El Nino–Southern Oscillation (ENSO), or major ocean currents that significantly affect sea surface height along ALKI-I. Activation of EOF1 leads to coherent SWH changes across the entire area, highlighting the role of broad-scale oceanographic dynamics. The second pattern (EOF2), explaining 35% of the variance, captures a less dominant but still substantial component of variability. This pattern may be linked to regional oceanographic processes, including seasonal variations, upwelling, or interactions between ocean currents and the local bathymetry near ALKI-I. Unlike EOF1, EOF2 displays a more localized and complex spatial structure, suggesting its influence is

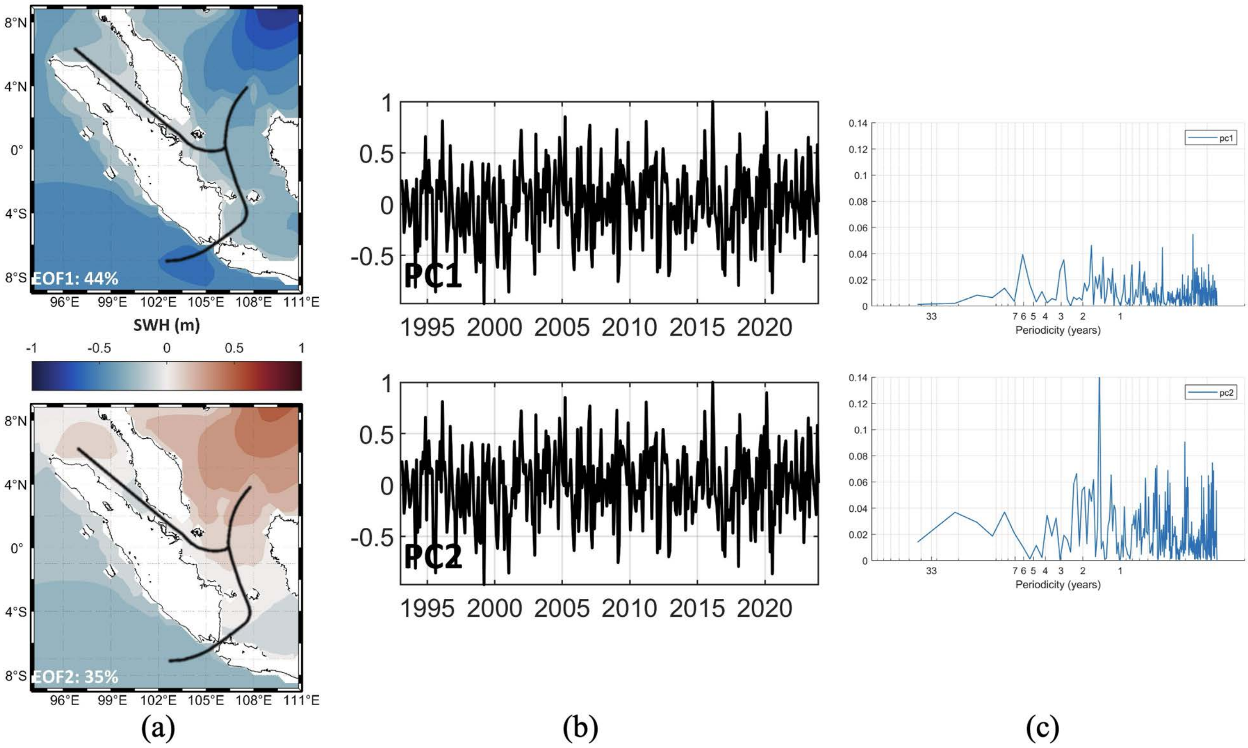

Figure 6. Results of EOF analysis for ALKI-I from January 1993 to December 2023: (a) spatial patterns, (b) temporal variability, and (c) periodicity analysis.

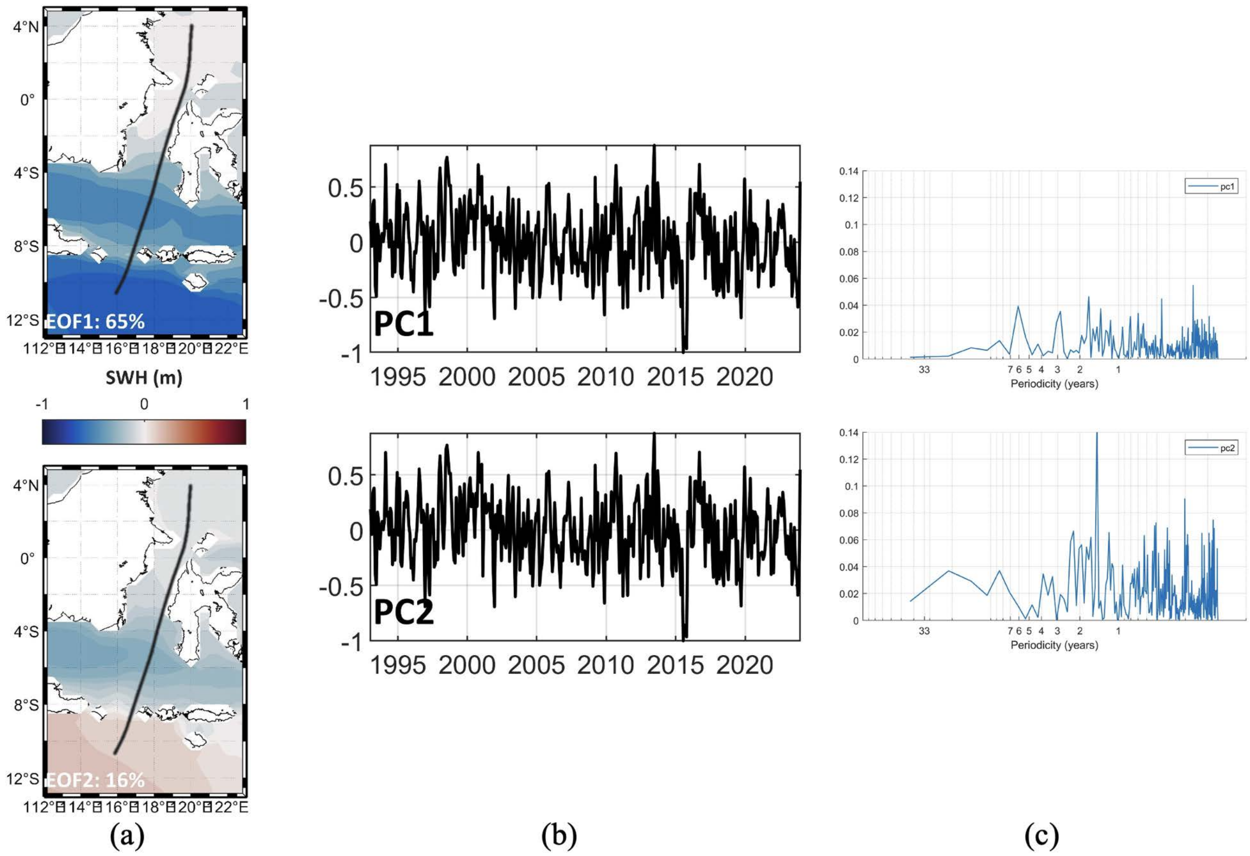

Figure 7. Results of EOF analysis for ALKI-II from January 1993 to December 2023: (a) spatial patterns, (b) temporal coefficients, and (c) periodicity.

spatially heterogeneous but still significant for SWH dynamics in the region.

The EOF analysis of SWH data in ALKI-II reveals two principal patterns of variability explaining a total of 81 % of the variance (Figure 7). EOF pattern 1, contributing 65 %, dominates SWH variability in this region. This pattern is likely associated with large scale oceanographic and atmospheric phenomena such as major ocean currents, broad sea surface temperature anomalies, and global atmospheric pressure systems. In the Indonesian context, it may relate to the Indonesian Throughflow (ITF) transporting water masses from the Pacific to the Indian Ocean, as well as the influence of monsoonal winds and global climate modes like El Niño and La Niña. EOF pattern 2, accounting for 16 % of the variance, captures a secondary but still significant component of variability. This pattern likely reflects regional to local scale processes, including local currents, coastal upwelling, and responses to changes in wind and rainfall. In ALKI-II, EOF 2 may highlight complex interactions between regional circulation and coastal dynamics, influenced by seabed topography and the archipelagic setting of Indonesia.

The results of the EOF analysis for SWH data in ALKI-III reveal two main patterns of variability, representing in total 80% of the data variance (Figure 8). EOF pattern 1, accounting for 54%, is the dominant pattern and likely reflects major drivers such as global climate variability (e.g., El Niño and La Niña) and seasonal fluctuations that broadly affect the ALKI-III region. This pattern is characterized by consistent, large scale variations linked to changes in oceanic and atmospheric circulation. EOF pattern 2 contributes 26% of the variance and captures regional or local variability, potentially associated with specific ocean currents, spatial differences in sea surface temperature, or other localized environmental factors. Although less dominant than EOF 1, EOF 2 remains important for understanding finer scale sea surface height dynamics in the region.

The global impact of the El Niño–Southern Oscillation (ENSO) drives interannual variations in Global Mean Sea Level (GMSL), particularly across the tropical and subtropical Pacific Ocean (Holbrook et al., 2020). Characterized by the periodic emergence of warmer surface waters in the equatorial eastern Pacific every 2–7 years (Figure 10), ENSO represents a major component of global climate variability (Amirudin et al., 2020). Its influence on Indonesian seas is considerable. The Indonesian Throughflow (ITF) serves as the principal oceanic conduit linking the Pacific and Indian Oceans (Edwards et al., 2020), channeling Pacific waters through the Indonesian archipelago. Due to the large

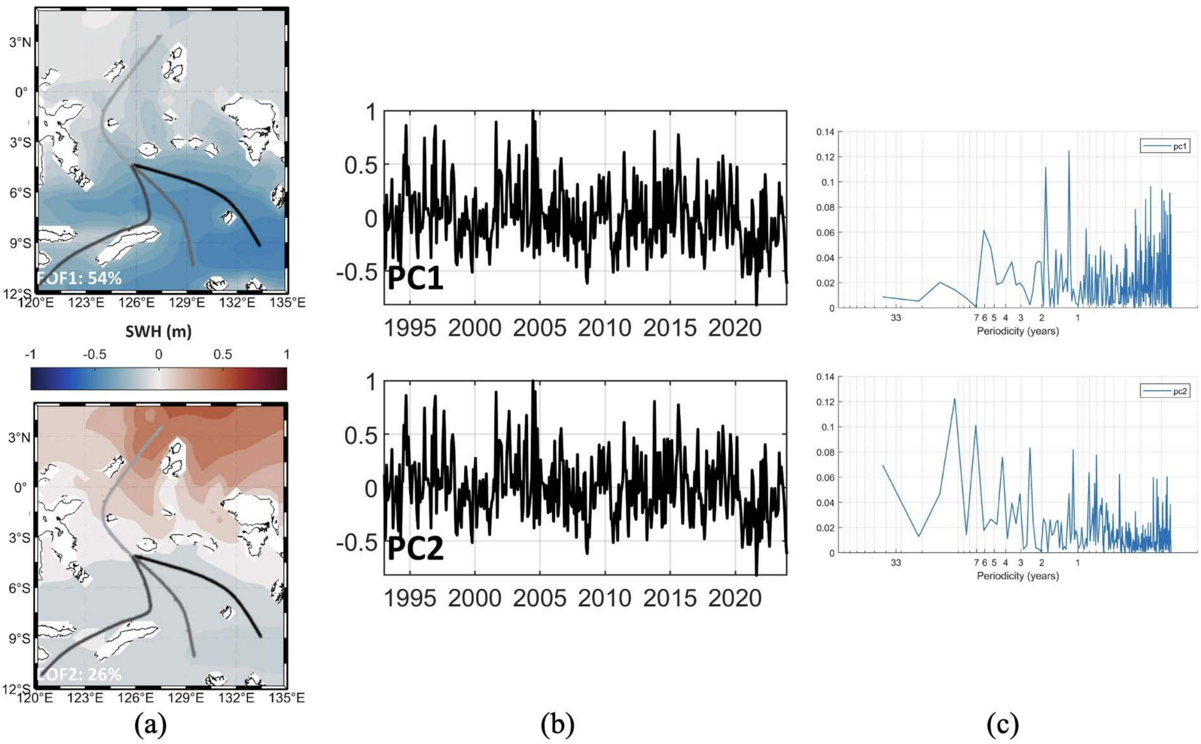

Figure 8. EOF analysis results for ALKI III from January 1993 to December 2023: (a) spatial pattern, (b) corresponding temporal component, and (c) periodicity analysis.

interannual sea level variability associated with ENSO across the western Pacific and eastern Indian Ocean, sea levels around Indonesia are strongly affected by ENSO events. Typically, El Niño episodes lead to reduced sea level and lower sea surface temperatures in Indonesian waters, whereas La Niña brings stronger trade winds, elevated sea levels, and warmer sea surface temperatures (Sanchez-Cabeza et al., 2022).

ENSO events have repeatedly affected Indonesian waters, with the most intense El Niño and La Niña episodes recorded in 1997–1998 and 2011, respectively (Figure 11). Another notable feature is the pronounced sea level decline observed since 2013, which coincided with a recent El Niño episode. In contrast, significant positive sea level anomalies were primarily observed in the Flores Sea and northern Java Sea during 2010 and 2013 (Figure 12). The characteristics of sea surface height (SSH) in Indonesian waters exhibit strong geographic and bathymetric variability, following clear seasonal patterns. In open and deeper oceanic areas, particularly within ALKI-III, SSH variations show higher sensitivity to seasonal cycles, extreme SSH events, and El Niño–La Niña phases (Dangendorf et al., 2024). In contrast, closed seas, narrow straits and shallow shelf regions such as those along ALKI-I and ALKI- II tend to display less pronounced variability. Across the Indonesian seas, SSH typically ranges from 0–4.5 m. The minimum sea level anomaly (SLA) patterns occur over western Indonesian waters between April and August, whereas the highest SLA patterns are observed from September to March, broadly coinciding with the dry season (April–October) and the wet season (September–March).

The difference in SSH between the tropical northwest Pacific (NWP) region and the southeastern Indian Ocean (SEI) region effectively represents ITF transport. Large-scale surface winds play a crucial role in sustaining these SSH differences across the tropical Pacific and Indian Oceans. The climatological surface circulation associated with the Hadley and Walker circulations, located east of the tropical Pacific, acts to accumulate surface water (Fujita et al., 2010). This leads to higher SSH in the NWP region compared to the relatively lower SSH in the SEI region. Because the SSH in the SEI region is affected by the Indian Monsoon, seasonal reversals of surface winds contribute to seasonal variations in the ITF. Beyond the climatic perspective, surface wind modulations on interannual and decadal timescales can induce ITF fluctuations by changing the SSH differences between the NWP and SEI regions. However, basin scale surface wind anomalies driven by ENSO and Indian Ocean Dipole (IOD) events, despite the usual occurrence of positive IOD alongside El Niño and negative IOD with La Niña, show limited effect on SSH differences between the NWP and SEI regions. Furthermore, the subtle effects of interannual wind variability on SSH anomalies are further diminished during recent interdecadal periods, particularly between 1993–2000 and 2000–2006 (Figures 10–13). These findings suggest limited influence on SSH differences across the Indonesian archipelagic straits during these interdecadal periods.

In contrast to the earlier assumption of similar behavior on interannual and decadal timescales, surface wind variations in both basins exhibit relative independence over a longer period (1959 to 2009) (Nidheesh et al., 2013). These studies also indicate distinct dominant spatial patterns of simulated SSH anomalies (SSHA) in ocean general circulation models across interannual and decadal timescales. The principal SSHA modes on interannual timescales display comparable loading with the same polarity across the Indonesian Archipelago straits, resulting in largely unchanged SSH differences between the NWP and SEI regions (Kara, 2016). By contrast, at the decadal timescale, the dominant mode shows significant loading in the NWP region with a less pronounced effect in the SEI region. Therefore, differences in SSH within the Indonesian Archipelago straits linked to this decadal main mode may represent a primary driver of decadal ITF variations, suggesting that the NWP and SEI regions contribute differently to these decadal changes.

Safety of Shipping and Maritime Transportation

Several key points emerge regarding the current state of safety management in Indonesia's Archipelagic Sea Lanes. Existing shipping safety arrangements in Indonesia require enhancement, particularly in terms of vessel navigation capabilities (Fatmawati et al., 2023). This highlights the need to address operational and regulatory challenges to ensure the safety of commercial maritime activities within the region. Furthermore, ships transiting Indonesian waters must adhere to internationally recognized navigational rules to minimize the risk of accidents (Sebastian et al., 2014).

The Archipelagic Sea Lanes, as specifically defined routes through the Indonesian archipelago (Lestari, 2020), play a vital role in ensuring the unimpeded passage of foreign vessels engaged in shipping and aviation operations. As outlined in the Semaphore, Indonesia bears a critical obligation to guarantee the safe and expeditious transit of ships through its waters without hindrance or coercion (Forward, 2009), underscoring the government's role in maintaining navigational safety. In addition, substantial technical and hydrographic efforts are necessary to support maritime safety (Nugroho, 2023), as these initiatives contribute to a better understanding of local marine conditions and operational security.

The international recognition of these sea lanes further demonstrates their global importance. Through diplomatic engagement and collaboration under the International Maritime Organization (IMO), maritime nations, including Indonesia, have secured largely unrestricted access to archipelagic waters, reflecting the sea lanes' significance for global maritime trade. Nevertheless, gaps remain within the legal framework governing foreign vessel transit, which, although clear in addressing innocent passage, still lacks specific provisions to manage potential infringements by foreign ships.

Another important aspect relates to informed and safe decision-making based on environmental conditions. Recognizing the characteristics of local weather, particularly wave energy, is crucial; when used as a parameter for navigation, calm seas can support increased cruise activities, while strong winds and high waves require careful planning. In such conditions, it is necessary to ensure that ships have suitable dimensions and design to navigate safely (Anggara et al., 2018).

The Indonesian Archipelagic Sea Lanes serve as vital corridors for global maritime trade, highlighting the need to ensure both safe and efficient navigation. Despite robust international frameworks and national commitments, gaps in implementation remain. Addressing these challenges requires integrated efforts to modernize maritime infrastructure, enhance hydrographic data quality, and improve maritime domain awareness. Strengthening these aspects will reinforce Indonesia's role as a reliable maritime nation and help safeguard the security and continuity of international shipping through its waters.

CONCLUSSIONS

The variability of significant wave height (SWH) along the Indonesian Archipelagic Sea Lanes (ALKI) shows distinct patterns across the three routes. In ALKI-I, SWH typically ranges from 1–2.5 m, with higher waves observed in the northern part during the Asian Monsoon season (December–February, DJF). In ALKI-II, wave conditions remain relatively calm throughout the year, generally ranging from 1–1.5 m. Meanwhile, ALKI-III experiences higher waves in the north during DJF and in the south during the Australian Monsoon (June–August, JJA), with SWH ranging from 1–2 m. In open ocean areas such as the Indian Ocean, SWH can increase further, as reflected in the extreme condition analysis showing outer Indonesian waters occasionally reaching 2–3 m.

Wind variability in Indonesian waters is also shaped by the monsoonal cycle. During the Asian Monsoon, ALKI-I is characterized by winds corresponding to the 4th Beaufort scale, while ALKI-II and ALKI-III experience stronger winds exceeding 8 m/s and 9 m/s, respectively. In the Australian Monsoon, winds of the 4th and 5th Beaufort scale occur in the southern parts of all ALKI routes. The most extreme wind speeds, over 10 m/s, are recorded in the South China Sea, Arafura Sea, and Indian Ocean.

Rainfall distribution follows a similarly seasonal pattern. In DJF, precipitation in ALKI-I reaches 350–600 mm, while ALKI-II records values around 300–450 mm. ALKI-III, by contrast, sees peak rainfall of approximately 200–450 mm between April and July, though the Arafura Sea shows a pattern similar to ALKI-I and ALKI-II. The highest 90th percentile rainfall values, classified as very extreme by BMKG, are concentrated near the mouth of the Malacca Strait, Natuna Sea, and South China Sea (250–350 mm). Additional areas of extreme rainfall, reaching 150–250 mm, include the Karimata Strait, Java Sea, and Flores Sea.

Indonesia's strategic position as a major maritime nation traversed by these sea lanes brings significant responsibility for ensuring the safety of shipping and maritime transportation. This responsibility can be fulfilled by deepening the understanding of local metocean conditions, strengthening legal frameworks, enforcing regulations, and improving operational supervision.

Compared to previous studies, the present results may slightly underestimate wave and wind conditions in certain outer regions, which are more directly influenced by open ocean dynamics. This limitation may be attributed to the reliance on secondary data, which may not fully capture extreme events such as tropical cyclones, internal waves, squalls, or tsunamis. Therefore, stakeholders are advised to exercise greater caution when selecting vessels and determining navigation routes, especially during high-risk periods such as the Asian Monsoon season from December to February. Moreover, due to the potential for severe weather conditions to intensify wind and wave activity beyond normal levels, it is strongly recommended to supplement planning with more specific metocean studies and reliable weather forecasts to ensure safer and more informed maritime operations.

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