Coastal Processes Assessment of Mainland Kedah and Langkawi Island Shorelines: A Case Study

Ebrahim Al-Qadami, Mohd Adib Mohammad Razi, Syed Muzzamil Hussain Shah, Arman Mokhtar, Mahran Mahamud

***Abstract*—The wave, wind, and tidal processes are part of the complex dynamic system that play a crucial role in shaping the coastal and marine environment. Understanding these processes in a particular area is essential for predicting coastal changes, managing coastal resources, and developing strategies for climate adaptation. The present study investigates the wind, wave, and tidal climates along mainland Kedah and Langkawi Island shorelines which cover around 440 km. Wind and wave climates were assessed based on long-term data of 29 years (1991-2019) at two locations namely, northern and southern points, while the tide climate was investigated over two months period through 6 stations distributed along the study area. Results revealed that the predominant wind came from the northeast and northwest directions with maximum speeds of 16 m/s and 14 m/s at the northern and southern points, respectively. In terms of wave climate, the predominant wave direction was northwest with maximum wave heights of 3.5 m and 2.8 m at the northern and southern points, respectively. Wave condition was found to be calm during the inter-monsoon period with a calm percentage of more than 90%. This value reduced to around 58% during the southwest monsoon. The study area experienced mixed tide but predominant by semi-diurnal tide. Tide records showed that station TG5 that was located on the east coast of Langkawi Island experienced the highest tidal range of 2.55 m, while the lowest (2.09 m) was noticed to be at TG2 station which was located at the middle point of the mainland Kedah shoreline. Authors believe that the findings of this study are crucial for effective coastal management and planning where stakeholders can better anticipate coastal changes, optimize resource management, and develop adaptive strategies to mitigate the impacts of climate variability.**

***Index Terms*—Coastal changes, climate adaptation, marine environment, tidal processes**

I. Introduction

COASTAL areas play a major environmental role by acting as natural barriers that dissipate energy during storm events [1], [2], [3]. Besides their environmental functions, coastal areas assume a pivotal role in the social, economic, and political development of most nations [4]. Their economic values have increased significantly especially with the increment in populations, industries, and recreational activities in these areas [5]. These areas are projected to complex natural dynamic phenomena and interactions [6] that shape the shorelines through several coastal processes such as sediment erosion and deposition [7], [8], wave action [9], tides [10], sea-level rise [11], [12], and coastal currents [13]. Human activities such as coastal development, harbours construction, and pollution have a significant effect on the coastal areas and can exacerbate or alter natural coastal processes [14], [15]. In this context, studying and evaluating the natural processes that have significant effects on the coastal areas are of the most importance in predicting coastal changes, managing coastal resources, and developing strategies for climate adaptation and mitigation [16], [17].

Malaysia has a long coastline of around 4,675 km which includes Peninsular Malaysia and East Malaysia (Sabah and Sarawak) [18] which required frequent assessment and evaluation to develop and adopt sustainable coastal management plans [19], [20]. Among the parameters that need to be assessed are wind, wave, and tide. Understanding these natural processes is vital for a wide range of purposes, from ensuring safety and environmental protection to supporting economic activities and infrastructure development [21]. Furthermore, understanding the present wind, wave, and tide conditions holds significance when evaluating the long-term and future changes attributed to human-induced factors. Recent research on climate change scenarios has indicated shifts in storm tracks and heightened storm frequency resulting in several changes in these processes' characteristics. Moreover, delving into the existing wind, wave, and tide climates would provide valuable information on the potential repercussions on coastal regions, such as coastal flooding, inundation, and erosion [22].

According to Sinnadurai et al. [18], the mean wave height at Peninsular Malaysia and East Malaysia shorelines ranges between 0.5 and 1.0m while the wave peak period ranges between 3 and 5 seconds. Mirzaei et al. [22] conducted a numerical study to investigate the wave climate in the southern region of the South China Sea (SCS) which is located on the northeast side of Peninsular Malaysia. The assessment was performed for the period of 31 years (1979-2009). According to their results, the mean significant wave height near the east coast of Peninsular Malaysia could reach up to 0.9m, while the mean 90th percentile wave height was reported to be around 4.5 m [22]. Furthermore, the study [22] reported that the lowest mean wave height occurred in March, April, and May, while the highest mean wave height occurred in December, January, and February which corresponds to the northeast monsoon season. Ariffin et al. [23] studied the morphodynamics of Terengganu Stat beaches

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under different monsoon seasons. According to their results, during the northeast monsoon season, the wave heights were significantly high which can approach 2.64 m and the storm condition was observed which resulted in coastline erosion. On the other hand, calm conditions and low wave heights (maximum value reached up to 0.7 m only) were noticed during the southwest monsoon season [23]. Arif et al. [24] studied the sea level rise along Peninsular Malaysia coastline using both tidal stations and satellite altimetry data over a period of 26 years (1994-2018). Results showed that the sea level experienced an upward trend with an average value of 3.2 and 4.14 mm/year for tidal and altimetric data, respectively. Among the total studied locations, sea level rise was the lowest at Pelabuhan Kelang station which is located on the southwest peninsular shoreline [24].

In the present study, wind, wave and tide climates along mainland Kedah and Langkawi Island shorelines which cover around 440km length were investigated. Wave and wind climates were assessed based on long-term data which was collected from two locations (northern and southern points) over a period of 29 years. Six tide measurement stations were installed along mainland Kedah (TG1, TG2, and TG3) and Langkawi Island (TG4, TG5, and TG6) shorelines to collect tidal data over a period of two months. The assessment was performed with the consideration of the seasonal changes at which 4 seasons were considered including (i) northeast monsoon (Nov., Dec., Jan., Feb., Mar.), (iii) inter-monsoon (Apr.), (iii) southwest monsoon (May., Jun., Jul., Aug., Sep.), and (iv) inter-monsoon (Oct.). It is believed that the obtained results presented in this study will help the local authorities of Kedah state in making informed decisions regarding coastal infrastructure, beach erosion, shipping routes, and other coastal activities.

II. METHODOLOGY

The present study investigates wave, wind, and tidal climates along the Kedah state coastal area to get deep insight into the conditions of their coastal processes. Long-term assessment for wind and wave climates was performed for different weather conditions including northeast monsoon, inter-monsoon (April and October), and southwest monsoon. On the other hand, a short-term assessment was performed for tidal conditions for both mainland Kedah and Langkawi Island.

A. Study Area

The study area covers the Kedah state coastal area with a total shoreline length of 440 km which includes, (i) mainland Kedah with a total length of 109km and (ii) Langkawi Island with a total length of 331km as shown in Figure 1. Long-term assessment of wind and wave climate was performed over a period of 29 years between 1991 and 2019, while the tide assessment was performed over two months (8th June to 31st July 2018).

B. Data Collection

Three different data sets were collected to assess the coastal process along the mainland Kedah and Langkawi Island coastline. Firstly, wind and wave data was collected from the Climate Forecast System Reanalysis (CFSR) database for the period of 29 years between 1991 and 2019. The data was acquired at two locations, namely (i) Northern point which is located at 99° 22.5’ E and 6° 24.042’ N at about 36 m chart datum (CD) depth situated about 30 km northwest of Langkawi Island, and (ii) Southern point which is located at 100° E and 5° 46.572’ N at about 34 m CD depth situated about 40 km northwest of Sungai Merbok River mouth as shown in Figure 1. Additional wind data was collected from Alor Setar and Pulau Langkawi airports’ wind stations which are operated by the Meteorological Department Malaysia (MMD). The data was used to evaluate the monthly mean surface wind speed as those airports are relatively close to the shoreline (see Figure 1).

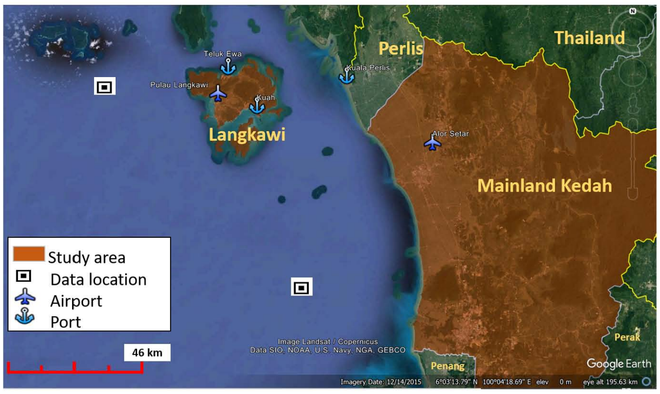

Fig. 1. Study area and data locations

Secondly, tidal data was collected from 6 different locations (see Table I), three along mainland Kedah and three around Langkawi Island as shown in Figure 2. Tidal gauges were installed at the targeted locations and the measurements were recorded for a period of around 2 months (8th June to 31st July 2018). The tidal stations at mainland Kedah were located at the rivers’ mouths and they were affected by both the tides and river discharges. The recorded data obtained from the tidal stations were compared with the data of the standard ports. For TG1, TG2, and TG3 Kuala Perlis port (see Figure 1) data were used for comparison, while Teluk Ewa and Kuah ports (see Figure 1) data was used to validate the tide records at TG4, TG5, and TG6.

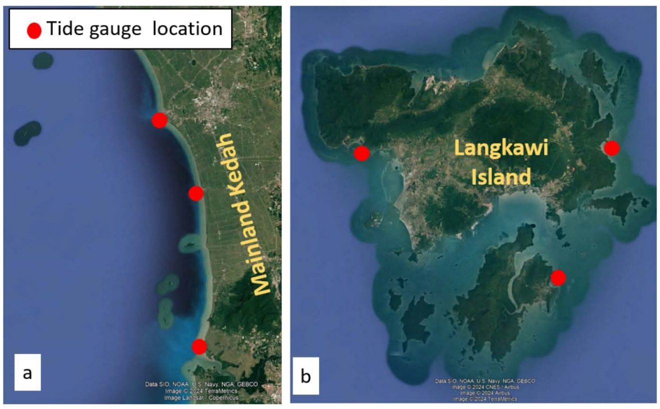

Fig. 2. Tide gauge locations (a) mainland Kedah and (b) Langkawi Island

TABLE I
COORDINATES OF THE TIDE MEASUREMENT STATIONS

Station ID	Latitude (N)	Longitude (E)
TG1	5° 40.76’	100° 22.32’
TG2	5° 58.37’	100° 21.16’
TG3	6° 7.38’	100° 17.60’
TG4	6° 14.72’	99° 51.62’
TG5	6° 22.05’	99° 54.61’
TG6	6° 21.90’	99° 41.08’

III. RESULTS AND DISCUSSION

A. Wind Climate

Based on the wind stations at Alor Setar and Pulau Langkawi Airports, it was found that the highest monthly mean wind speed was about 2.7 m/s at Alor Setar and 3.4 m/s at Pulau Langkawi. For both wind stations, the highest monthly mean speeds were noticed to occur during the inter-monsoon season. Also, it was noticed that the mean monthly wind speeds were higher in Pulau Langkawi Airport when compared with the reading in Alor Star Airport. This could be due to the existence of the central mountain chain in the peninsula. Table II summarizes the monthly mean wind speeds at Alor Setar and Pulau Langkawi wind stations.

Figure 3 depicts the annual wind roses in the northern and southern points where long-term data was collected (29 years). It can be noticed that the wind directions are primarily northeast and northwest for both locations, while the wind speed was significantly low in the south direction. At the northern point, the average and maximum wind speeds were found to be around 4.5 m/s and 16 m/s, respectively. On the other hand, the average and maximum wind speeds at the southern point were found to be 3.5 m/s and 14 m/s, respectively.

Seasonal wind roses were plotted at both stations (northern and southern points) for three different seasons, namely (i) northeast monsoon, (ii) inter-monsoon (April and October), and (iii) southwest monsoon as shown in Figure 4. At the northern point, it can be seen that the predominant wind direction is from the northeast during the Northeast Monsoon (see Figure 4), whilst from the northwest during Southwest and inter-monsoon (April and October) periods as shown in Figure 4b, c, d. At the southern point, the wind pattern is almost similar when compared with the northern points (see Figure 5) except for the inter-monsoon (April) where the predominant wind direction of the wind was from the southwest direction as shown in Figure 5b.

A comparison between the wind calm conditions between the northern and southern points at each season is presented in Figure 6. Generally, it can be noticed that calm wind condition is less than 7% during all seasons and in both points. This indicates that the wind is not calm all the time of the year. Also, it can be noticed that the calm wind percentage is always higher in the southern point during all seasons as shown in Figure 6. During the northeast monsoon season, the wind condition was found to be windy when compared with other seasons and with a calm percentage of 2.52% and 4.67% at the northern and southern points, respectively.

Along the study area, the wind was mainly governed by the monsoons, and it was found to be the primary wave-generating mechanism for wave incidents. The wind was much stronger during the monsoon periods especially the northeast monsoon season (November to March). The land and sea breezes were found to have an insignificant effect on the behaviour of diurnal wind. Sea breeze reached its maximum strength during mid-afternoon in the presence of strong surface heating. It went lower towards the evening when the thermal difference that drives the local circulation became negligible. The land breeze that normally started during the predawn period was considerably weaker.

B. Wave climate

Figure 7 shows the annual wave roses at the northern and southern points which represent the annual wave climate at the shorelines of Langkawi Island and mainland Kedah, respectively. The annual wave roses were developed based on the long-term data that were collected between 1991 and 2019. It can be noticed that the predominant wave direction was northwest at both points. This is due to the unlimited fetch length in this direction which extends until the Andaman Sea. Furthermore, it can be noticed that the wave height at the northern point close to Langkawi Island is higher when compared with the southern point close to mainland Kedah’s shoreline. The highest values of the wave heights can reach up to 3.5 m at the northern point and 2.8 m at the southern point.

Seasonal wave roses at the northern and southern points are illustrated in Figures 8 and 9, respectively. In general, the study area was noticed to be calm with a calm period (wave height less than 0.2 m) of more than 90% during the inter-monsoon (April and October) period at both locations. During the Southwest Monsoon, the waves approach from the northwest sector with a wave height that could reach up to more than 2.5 m as shown in Figure 8c and Figure 9c. The waves from the northeast sector during the Northeast Monsoon were noticed to be significantly lower in magnitude when compared to the Southwest Monsoon as shown in Figure 8a and Figure 9a. Table III summarizes the seasonal wave climate at the northern and southern points.

The study area experienced three different wave types, namely (i) wind-generated waves that propagate more or less in the wind direction and were highly influenced by the local wind fields. Wind waves were found to be relatively steep, irregular, and directional. This type of wave has significant effects on shaping the coastline as offshore movement of sediments is generated resulting in a generally flat shoreface and steep foreshore. (ii) Swell waves that have travelled beyond the generating area to reach the study area. Swell waves travel great distances over deep water after being generated by far-away wind fields. Swell waves are relatively long, moderate in height, regular, and unidirectional. The direction of propagation is dissimilar with the local wind direction. Swell waves tend to build up the coastal profile to a steep shoreface. (iii) Wake waves or ship wakes generated by passing marine vessels. This type of wave is almost similar to swell waves, and they experience considerable shoaling when approaching the coast.

The waves reaching Kedah’s mainland are typically wind waves while swell waves can be present at the islands

TABLE II
MONTHLY MEAN SURFACE WIND SPEEDS (M/S) AT ALOR SETAR AND PULAU LANGKAWI STATIONS

Season	Southwest Monsoon					Northeast Monsoon					Transition	
Months	May	June	July	August	September	November	December	January	February	March	April	October
Direction	SW	SW	SW	SW	SW	N	N	N	N	w	SW	SW
Alor Setar	2.4	2.2	2.4	2.5	2.5	1.2	1.2	1.5	1.6	1.3	2.7	2.6
Langkawi	3	3	3.3	3	3	2.5	3.3	3.4	3.2	2.7	3.4	2.8

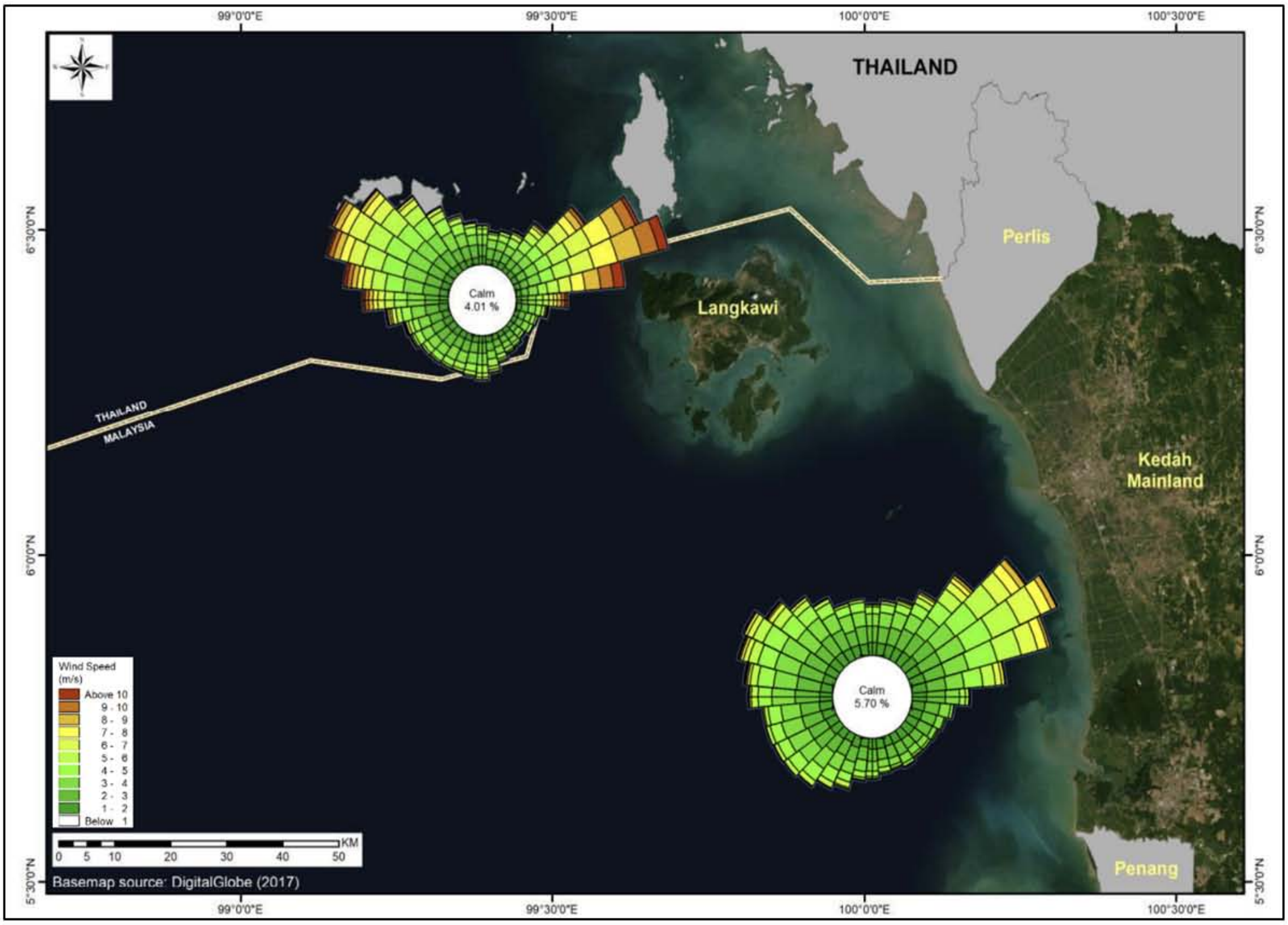

Fig. 3. Annual wind roses at Kedah shoreline

TABLE III
SUMMARY OF THE SEASONAL WAVE CLIMATE

Season	Location	Northeast monsoon	Inter-monsoon (April)	Southwest monsoon,	Inter-monsoon (October)
Predominant direction	Northern point	Northeast	Northwest	Northwest	Northwest
	Southern point	Northeast	Northwest	Northwest	Northwest
Maximum wave height (m)	Northern point	1.5	1	More than 2.5	2.5
	Southern point	1	1	More than 2.5	2
Calm percentage (%)	Northern point	65.14	93.35	58.39	92.53
	Southern point	71.75	93.65	58.82	92.92

especially Langkawi (on the northern side of the island where swell waves may dominate). Wake waves are more common near harbours or marinas.

C. Tide Climate

Understanding the timing and height of tides is essential for various purposes, including navigation, coastal management, beach safety, and activities such as fishing and boating. In the present study, tide data were collected at six stations of which 3 were located in mainland Kedah's shoreline, while the other 3 were located around Langkawi Island. Tidal reference which includes highest astronomical tide (HAT), mean high water spring (MHWS), mean high water neap (MHWN), mean sea level (MSL), mean low water neap (MLWN), mean low water spring (MLWS), and lowest astronomical tide (LAT) were measured and presented for

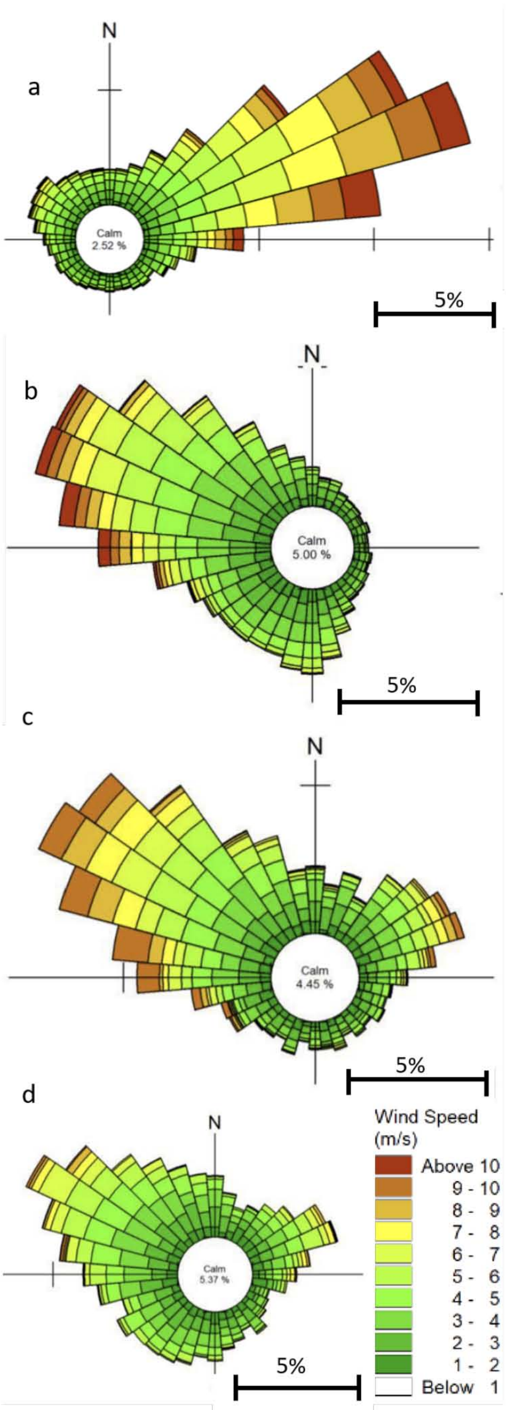

Fig. 4. Seasonal wind roses at Langkawi shoreline (northern point), (a) northeast monsoon, (b) southwest monsoon , (c) inter-monsoon (October) , and (d) inter-monsoon (April)

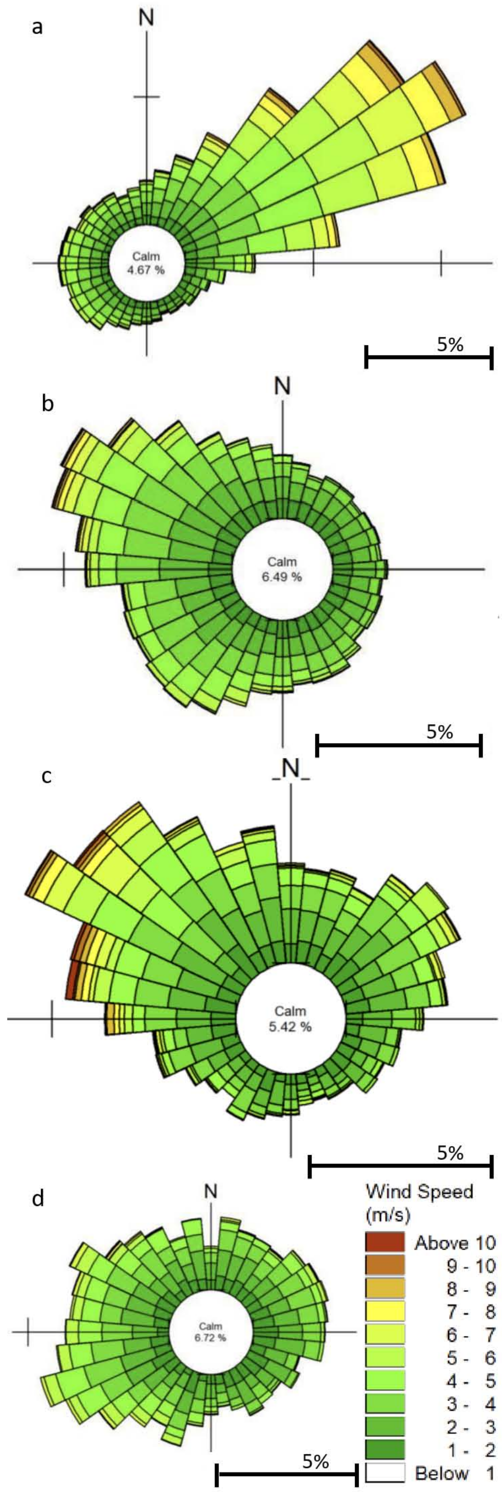

Fig. 5. Seasonal wind roses at mainland Kedah's shoreline (southern point), (a) northeast monsoon, (b) southwest monsoon, (c) inter-monsoon (October), and (d) inter-monsoon (April)

each tidal station is shown in Table IV. According to the results, it was noticed that station TG5 which was located at the east Langkawi Island shoreline experienced the highest tidal reference values when compared with other stations with maximum values of 3.414m for HAT, 2.938m for MHWS, 2.003m for MHWN, 1.641 for MSL, and 1.329m for MLWN. On the other side, station TG2 located at the middle point of the mainland Kedah shoreline experienced the lowest values of tidal reference as presented in Table IV.

The mean values of the tidal reference in mainland Kedah shoreline were found to be 3.01, 2.56, 1.78, 1.47, 1.20, and 0.41m for HAT, MHWS, MHWN, MSL, MLWN, and MLWS, respectively. On the other hand, the values along Langkawi Island were 3.15, 2.69, 1.84, 1.50, 1.19, and 0.35 for HAT, MHWS, MHWN, MSL, MLWN, and MLWS, respectively as shown in Figure 10. According to Figure 10, it can be observed that there were no significant differences between the tidal reference at mainland Kedah and Langkawi Island at which the difference in highest astronomical tide (HAT) was only 0.14 m.

The obtained tidal datums were compared with the nearby

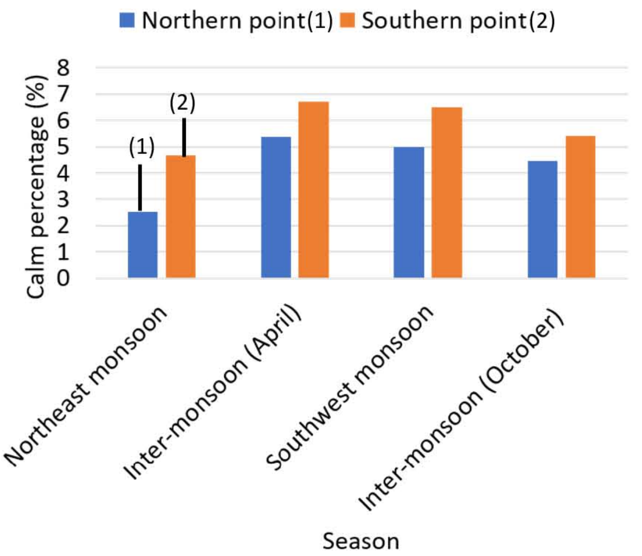

Fig. 6. Seasonal calm wind percentage comparison between northern and southern points

standard ports' records for validation purposes as shown in Table V. Tidal information in Table V was obtained from the Tide Tables for Malaysia 2020 published by the National Hydrographic Centre. In Langkawi Island, Kuah, and Teluk Ewa ports tidal data was used to check the records of the installed tidal station along the island shoreline (TG4, TG5, and TG6). In mainland Kedah, there is no standard port therefore the nearest port in Perlis State was used which is called Kuala Perlis Prot to validate the records of the other stations (TG1, TG2, TG3). The comparison process showed that the installed tidal stations' readings were in agreement with the recorded data at the standard ports.

TABLE IV
TIDAL PLANES AT TIDAL MEASUREMENT LOCATIONS (M)

Tidal plane	TG1	TG2	TG3	TG4	TG5	TG6
Highest astronomical tide (HAT)	3.13	2.92	2.99	3.07	3.41	2.97
Mean high water spring (MHWS)	2.65	2.42	2.61	2.61	2.94	2.53
Mean high water neap (MHWN)	1.83	1.71	1.82	1.80	2.003	1.74
Mean sea level (MSL)	1.54	1.36	1.49	1.44	1.64	1.41
Mean low water neap (MLWN)	1.29	1.08	1.22	1.13	1.33	1.13
Mean low water spring (MLWS)	0.49	0.33	0.40	0.32	0.39	0.33
Lowest astronomical tide (LAT)	0.00	0.00	0.00	0.00	0.00	0.00

In terms of tide type, it was noticed that the tides were mixed but predominantly semi-diurnal tides. The semi-diurnal can be characterized by two high tides and two low tides of approximately equal magnitude occurring during a 24-hour period. Table VI summarizes the maximum and mean tide ranges of all stations including the existing standard ports.

TABLE V
REFERENCE TIDAL DATUM LEVELS IN THE VICINITY OF THE STUDY AREA (M)

Tidal plane	Water level (m)		
	Kuala Perlis	Kuah	Teluk Ewa
Highest astronomical tide (HAT)	3.69	3.26	3.56
Mean high water spring (MHWS)	2.8	2.74	3.07
Mean high water neap (MHWN)	1.96	1.94	2.18
Mean sea level (MSL)	1.68	1.64	1.82
Mean low water neap (MLWN)	1.4	1.33	1.46
Mean low water spring (MLWS)	0.56	0.53	0.56
Lowest astronomical tide (LAT)	0	0	0

TABLE VI
TIDAL RANGES AT THE STANDARD PORTS AND THE LOCATIONS OF TIDE MEASUREMENT STATIONS IN THE VICINITY OF THE STUDY AREA (M)

Location	Maximum tidal range	Mean tidal range
K. Perlis	2.24	0.56
Kuah	2.21	0.61
T. Ewa	2.59	0.72
TG1	2.16	0.54
TG2	2.09	0.63
TG3	2.2	0.59
TG4	2.29	0.67
TG5	2.55	0.67
TG6	2.2	0.61

Comparing Lowest Astronomical Tide (LAT)/Chart Datum (CD) with NGVD (National Geodetic Vertical Datum) is crucial for integrating geodetic and tidal data in coastal studies. LAT, a tidal datum, represents extreme low-water levels, while NGVD, a geodetic datum, approximates mean sea level. This comparison ensures consistency in bathymetric mapping, tidal range analysis, and coastal infrastructure design, where both land-based elevations and tidal extremes are relevant. Table VII compares tidal planes relative to Lowest Astronomical Tide (LAT)/Chart Datum (CD) and National Geodetic Vertical Datum (NGVD) across the six tidal gauge stations (TG1–TG6). It highlights how the two reference systems differ at each tidal plane. LAT is consistently lower than NGVD, as shown by the negative NGVD values for LAT across all stations. HAT represents the highest tidal level, with TG5 having the greatest HAT in both LAT/CD (3.414 m) and NGVD (2.023 m), while TG2 has the lowest (2.915 m in LAT/CD and 1.724 m in NGVD). MSL in NGVD is close to zero at all stations, reflecting its approximation of historical mean sea level, while in LAT/CD it varies slightly across stations, indicating local tidal and bathymetric differences. These differences underline the importance of

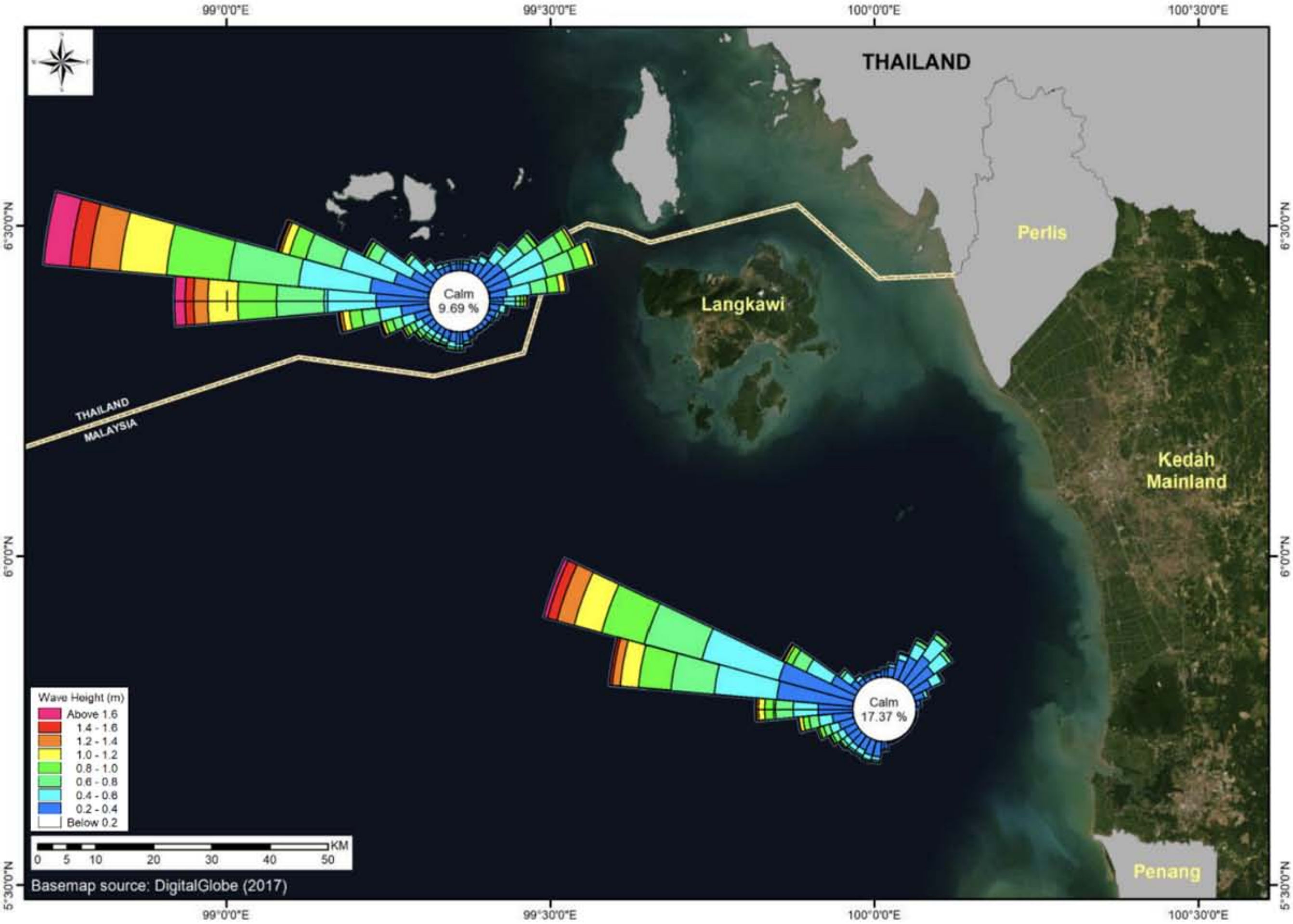

Fig. 7. Annual wave rose at Kedah's shoreline

selecting the appropriate datum for navigation, infrastructure design, and flood risk assessments, as tidal ranges and extremes vary significantly between LAT/CD and NGVD.

IV. Socioeconomic benefits

There are significant socioeconomic impacts of such studies focusing on the wind, wave, and tidal climate on the coastal areas. Especially, because these regions are at the forefront of both renewable energy development and the effects of climate change. Such studies can help guide policy, infrastructure, and economic planning to promote sustainable development and climate resilience. Climate studies on wind, tidal, and wave energy highlight their potential to assess the long-term viability and efficiency of renewable energy sources, contributing to more stable energy production and reducing reliance on imported fossil fuels, thereby benefiting local economies by lowering energy costs. Additionally, climate studies guide public and private investments in infrastructure by providing accurate data on tidal patterns, wind speed, and wave dynamics, reducing risks for investors and encouraging capital flow into renewable energy projects like offshore wind farms. Moreover, such studies can influence tourism by ensuring that renewable energy infrastructure complements, rather than detracts from, the coastal aesthetics, preserving the balance between energy development and the tourism and recreation sectors vital to many coastal economies.

Environmentally, such studies help coastal areas prepare for climate change impacts like sea-level rise and extreme weather, promoting resilient infrastructure. They also balance the growth of renewable energy with ecosystem preservation, protecting marine life and biodiversity. In terms of policy, climate studies guide sustainable coastal development, disaster risk reduction, and equitable access to clean energy, ensuring that vulnerable communities benefit from job creation and improved living standards. Furthermore, they support economic diversification by opening new markets in renewable energy and fostering opportunities for energy exports, contributing to the long-term economic resilience of coastal areas.

V. Conclusion

In this study, wind, wave, and tide climates were investigated along the Kedah State shoreline which covers around 440km in length. Wind and wave climate analysis was performed based on long-term data which was collected at two locations (northern and southern points) from the Climate Forecast System Reanalysis (CFSR) database for the period of 29 years (1991 to 2019). Tide data was collected through water level stations which were installed at 6 different locations of which three were located along the mainland Kedah shoreline, while the remaining three were located around Langkawi Island. Results revealed that the wind direction and speed were mainly governed by the

TABLE VII
TIDAL PLANES RELATIVE TO LAT/CD AND NGVD TIDAL DATUM (M)

Tidal Plane	TG1		TG2		TG3		TG4		TG5		TG6	
	LAT	NGVD	LAT	NGVD	LAT	NGVD	LAT	NGVD	LAT	NGVD	LAT	NGVD
HAT	3.127	1.772	2.915	1.724	2.990	1.558	3.070	1.909	3.414	2.023	2.970	1.793
MHWS	2.650	1.295	2.422	1.231	2.608	1.176	2.605	1.444	2.938	1.547	2.530	1.353
MHWN	1.828	0.473	1.708	0.517	1.815	0.385	1.795	0.634	2.003	0.612	1.736	0.559
MSL	1.544	0.189	1.364	0.173	1.491	0.059	1.444	0.283	1.641	0.250	1.410	0.233
NGVD	1.355	0.000	1.191	0.000	1.432	0.000	1.161	0.000	1.391	0.000	1.177	0.000
MLWN	1.290	-0.065	1.079	-0.112	1.221	-0.211	1.129	-0.032	1.329	-0.062	1.126	-0.051
MLWS	0.488	-0.867	0.328	-0.863	0.403	-1.029	0.319	-0.842	0.388	-1.003	0.329	-0.848
LAT/CD	0.000	-1.355	0.000	-1.191	0.000	-1.432	0.000	-1.161	0.000	-1.391	0.000	-1.177

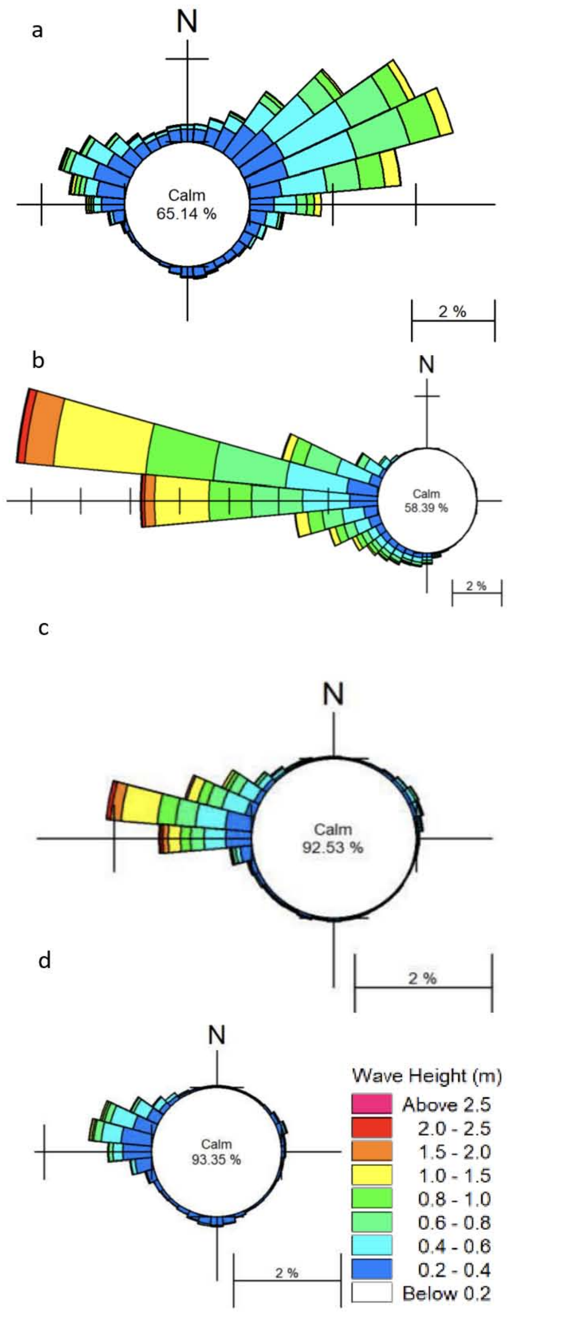

Fig. 8. Seasonal wave roses at Langkawi shoreline (northern point), (a) northeast monsoon, (b) southwest monsoon , (c) inter-monsoon (October), and (d) inter-monsoon (April)

monsoon seasons which include northeast and southwest monsoons. Annual wind rose showed that the wind directions were primarily northeast and northwest at both locations at which the maximum wind speed could reach up to 16 m/s at the northern point and 14 m/s at the southern point. On the other hand, the predominant wave direction was found to be the northwest direction where the maximum wave heights at northern and southern points were found to be 3.5 m and 2.8 m, respectively. The wave heights approached the maximum values during southwest monsoon seasons, while the waves can be considered calm i.e., wave height is less than 0.2 m during the inter-monsoon season (April and October). The wave type in the study area was noticed to be mainly wave-generated waves, however, swell and ship wake generated waves were observed as well. Tides in the study area can be classified as semi-diurnal tides with a maximum tidal range of 2.55 m at Langkawi Island and 2.09 m at mainland Kedah shorelines. The authors believed that the outcomes of the present study will help the local authorities of Kedah state in making informed decisions regarding coastal infrastructure, beach erosion, shipping routes, and other coastal activities. Besides, the presented results are critical for mitigating the impacts of sea-level rise and extreme weather events in coastal areas.

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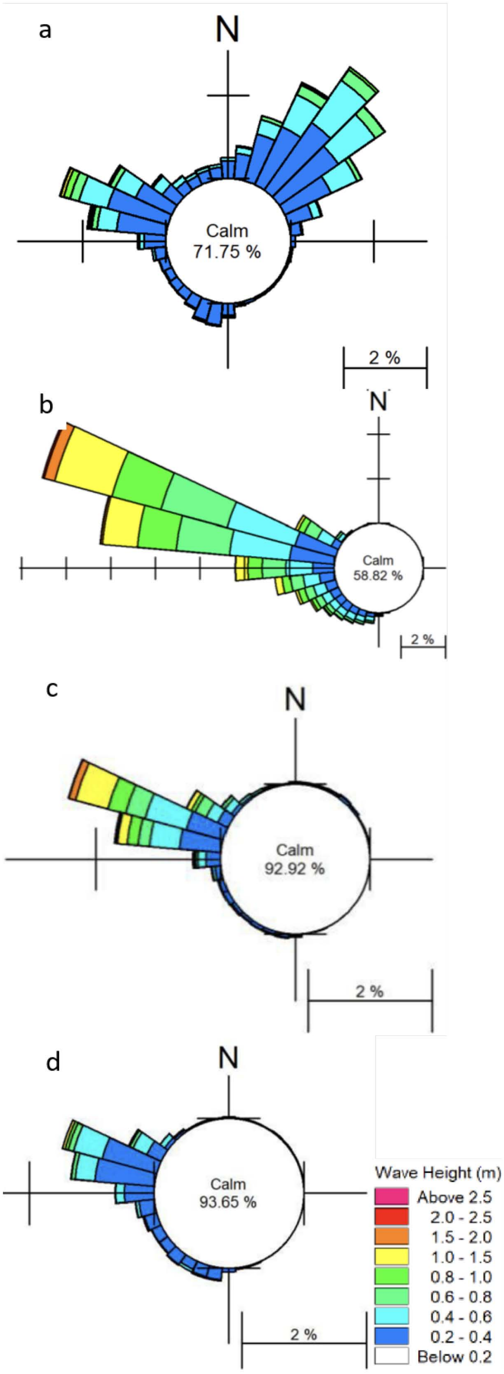

Fig. 9. Seasonal wave roses at Mainland Kedah shoreline (southern point), (a) northeast monsoon, (b) southwest monsoon , (c) inter-monsoon (October), and (d) inter-monsoon (April)

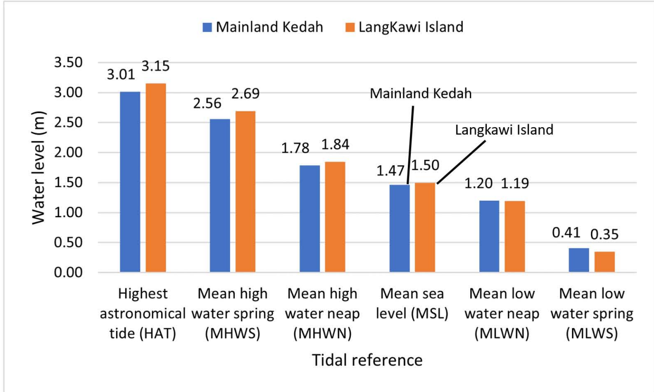

Fig. 10. Mean values of the tidal reference in Mainland Kedah and Langkawi Island shorelines

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