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Wave Regime of Vietnamese Waters on the Basis of Numerical Modeling and Field Measurements

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This paper presents results of research of the wave regime in Vietnamese waters (South China Sea) based on the data of numerical modeling data using the WAM model (WAVE Modeling). The model domain covers the basin of the South China Sea (SCS). The bathymetry of the SCS used in the model is based on the ETOPO5 digital database. Wind parameters are based on the six-hour NCEP/NCAR reanalysis data with a resolution of $\Delta X = \Delta Y = 0.25°$ over the period 1979–2021. The field wave data measurements were collected by the Institute of Oceanography of Vietnam Academy of Science and Technology in the southern central Vietnamese waters in 2013. The statistical data of computed wave characteristics for the period of 43 years (1979–2021) illustrate that the main wave direction in Vietnamese waters was NE during the Northeastern (NE) monsoon, and in the opposite direction during the Southwestern (SW) monsoon. The NE monsoon wave was more dominant than that of the SW monsoon wave. Recurrence frequency (%) of significant wave height H_s >1.0 m (H_s – significant wave height is an average of 1/3 the largest of serial waves relative to average seawater level) greater than 50% covered the northeastern, central region of the SCS, and central Vietnamese coast. The wave recurrence frequency in the Gulf of Tonkin and Gulf of Thailand was <40% and <30%, respectively. The central Vietnamese coast from Ly Son Island to Phu Quy Island was the strongest affected by wave action. The recurrence frequency of the maximum significant wave height H_s >3.5 m was greater than 1.5%. The Gulf of Tonkin (Bach Long Vi Island) and the Gulf of Thailand (Tho Chu Island) were less affected by wave action than the central Vietnamese coast: the recurrence frequency of the maximum wave height (H_s>3.5 m) was less than 0.1%. Phu Quy and Con Dao Islands were more influenced by wave action during both seasons than the central coast of Vietnam.

Keywords: Vietnamese waters, South China Sea (SCS), wave regime, significant wave height, monsoon, WAM model.

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Introduction

The South China Sea (SCS) is located in Southeast Asia, with coordinates 0°–25°N and 99°–121°E. It is connected to the East China Sea by the Taiwan Strait; to the Pacific Ocean by the Luzon Strait; to the Sulu Sea by the Mindoro Strait; to the Java Sea by the Gasper and Karimata Straits; and to the Indian Ocean by the Strait of Malacca [*Chu et al.*, 1999]. The topography of the SCS is complex, including the Sunda Shelf in the south-southwest; the continental shelf in the north, (from the Gulf of Tonkin to the Taiwan Strait); and a deep basin in the center Figure 1. The SCS is strongly affected by monsoon winds and tropical cyclones. The weather in the SCS is dominated by the northeast monsoon (November–March), and the southwest monsoon (June–August).

Determination of the wave regime has an important role for marine economic activities. Pro-

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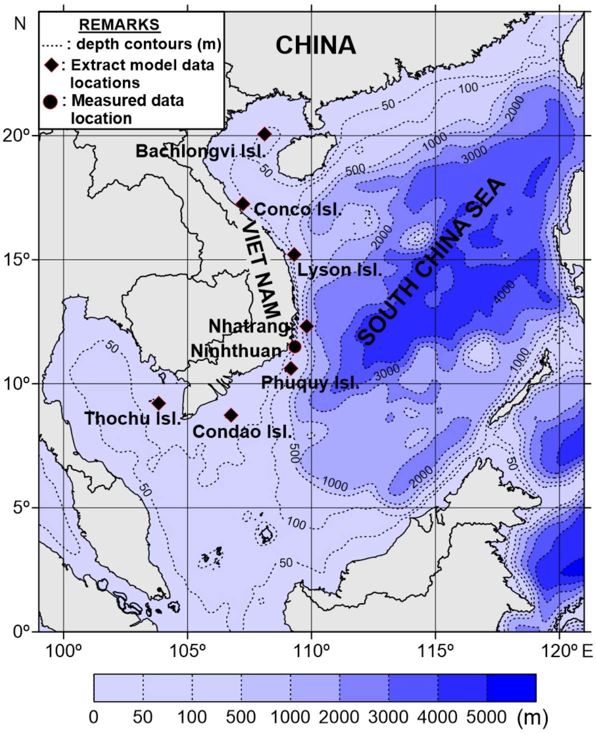

Figure 1: Study locations and topography of the South China Sea.

cesses of formation, development, and dissipation of wave parameters depend on the varied processes of wind and related conditions such as current and topography which are still a shortcoming for studying the wave regime in the SCS. The comparison of various wave models to get the advantage and shortcoming of each model was done by SWAMP [*SWAMP Group and others*, 1985]. The compared results show the advantage of the third-generation wave models. Prediction of waves during typhoon activity was done by *Young* [1988]. One-day wave forecasts based on artificial neural networks were studied by *Londhe and Panchang* [2006]. An overview of the numerical and neural networks Accosts of ocean wave prediction were carried out by *Mandal and Prabaharan* [2003]. *Le et al.* [2004] used the Young model [*Young*, 1988] to estimate maximum wave characteristics during typhoon weather in the SCS. A study on the numerical simulation of the wave field in the SCS using WAVEWATCH III [*Tolman*, 1991] was done by *Zhou et al.* [2014]. In *Le* [2006], the WAM model [*Guenther et al.*, 1992; *WAMDI Group*, 1988] was used to estimate wave characteristics in the SCS. In addition, studies on the distribution features of wave characteristics in the SCS for different wind conditions such as monsoons and typhoon were done by *Chu and Cheng* [2008], *Mirzaei et al.* [2013], *Shao et al.* [2018], and *Vlasova et al.* [2020]. *Le and Nguyen* [2018] carried out a study on the seasonal distribution features of wave characteristics based on measured waves in the coastal waters of Ninh Thuan Province, Central Vietnam coast. Typhoons generate surface waves and inertial oscillations. The generation of inertial oscillations by propagating typhoons in the Northwest Pacific has been studied in [*Morozov and Velarde*, 2008].

The WAM (Wave Modeling) model is a third-generation wave model [*Guenther*, 2002; *Guenther et al.*, 1992]. The model permits to simulate the progress of wave spectrums, especially in the condition of typhoons, fronts when the wind field changes in both directions and speeds. The model enables it to run on any given regional or global grid with a prescribed topographic dataset. The grid resolution of the model can be arbitrary in space and time. A latitudinal-longitudinal or a Cartesian grid of wave propagation can be done. The model output parameters are the significant wave heights, mean wave directions and frequencies, the swell wave heights and mean directions, and wind stress fields. The model can also run in deep and shallow water, including refraction effects and current interactions. The model permits the source terms and the propagation to be computed with different methods and time steps. The wind time step can be selected arbitrarily. Subgrid squares can be run in a nested mode and the spectra can be output at the boundaries of a subgrid. The WAM model has been applied at worldwide institutions and also for operational applications. Another third-generation ocean wind-wave model, WAVEWATCH-III [*Tolman*, 1991], was applied to investigate wind-wave characteristics.

Vietnam is located on the west coast of the SCS with a coastline of approximately 3200 km and islands, and a large population lives along the coast or adjacent coastal low land areas. Therefore, estimation of the wave regime of Vietnamese waters has an important role for marine economic sustainable development, including maritime, fishing, mariculture, tourism, design of hydro-structures, environmental protection, etc. The Figure 1 shows the study locations and topography of the SCS.

Material and Method

Materials

The modeled domain covers the area 99°–121°E and 0°–25°N with resolution of 0.25°×0.25° in spacing. The topography of the SCS was collected from *National Geophysical Data Center* [1993] with a resolution of 5′ (≈9 km). Wind data from 1 January 1979 to 31 December 2021 at six hourly intervals with a resolution of 0.25°×0.25° were collected from the website: `https://cds.climate.`

copernicus.eu/cdsapp#!/search?type=dataset (for 43 years of data).

Measured wave data was collected off the Ninh Thuan province coast at a water depth of about 20 m using an AWAC wave recorder during 2013. The field survey of wave characteristics was carried out in the framework of the Contract (No. 142/hd-tv2-p02 on 7 June 2012) between the Institute of Oceanography and Vietnam Electricity (EVN), and Power Engineering Consulting JSC 2 (PECC2). This project is for the Environmental Impact Assessment (EIA) of Ninh Thuan-1 Nuclear Power Plant [*Le and Nguyen*, 2018].

Computation methods

Estimation of wave characteristics in the SCS were carried out by the WAM Cycle 4.5 model [*Guenther*, 2002]. The evolution of the two-dimensional ocean wave spectrum $F(f,\theta,\phi,\lambda,t)$ with respect to frequency f and direction θ (measured clockwise relative to true north) as a function of latitude ϕ and longitude λ on the spherical Earth is governed by the transport equation:

$$\frac{\partial F}{\partial t}+(\cos\phi)^{-1}\frac{\partial}{\partial\phi}(\dot{\phi}\cos\phi F)+\frac{\partial}{\partial\lambda}(\dot{\lambda}F)+\frac{\partial}{\partial\theta}(\dot{\theta}F)=S, \quad (1)$$

where: S – the net source function describing the change of energy of a propagating wave group, and represents the rates of change of the position and propagation direction of a wave packet traveling along a great circle path.

$$\dot{\phi}=\frac{d\phi}{dt}=vR^{-1}\cos\theta, \quad (2)$$

$$\dot{\lambda}=\frac{d\lambda}{dt}=v\sin\theta(R\cos\phi)^{-1}, \quad (3)$$

$$\dot{\theta}=\frac{d\theta}{dt}=v\sin\theta\tan\phi R^{-1}. \quad (4)$$

Here,

$v=g/4\pi f$ denotes the group velocity,

g – the acceleration of gravity,

R – the radius of the Earth.

The equations (1)–(4) apply to waves in water of infinite depth.

The generalization of the standard Cartesian geometry transport equation to the spherical geometry form (1) from the energy conservation equation for the spectral density $\hat{F}(f,\theta,\phi,\lambda)$ with respect to the four-dimensional phase space (f,θ,ϕ,λ).

$$\frac{\partial\hat{F}}{\partial t}+(\cos\phi)^{-1}\frac{\partial}{\partial\phi}(\dot{\phi}\cos\phi\hat{F})+\frac{\partial}{\partial\lambda}(\dot{\lambda}\hat{F})+\frac{\partial}{\partial\theta}(\dot{\theta}\hat{F})=S \quad (5)$$

Here $\hat{F}$ is related to the normal spectral density F with respect to a local Cartesian frame (x,y) through

$$\hat{F}(\mathrm{d}f\,\mathrm{d}\theta\,\mathrm{d}\phi\,\mathrm{d}\lambda)=F(\mathrm{d}f\,\mathrm{d}\theta\,\mathrm{d}\phi\,\mathrm{d}\lambda), \quad or\ \hat{F}=FR^2 cos\phi. \quad (6)$$

Substitution of (6) into (5) yields (1).

The structure of the transport Equations (1)–(4) carries over to the finite depth. However, modifications need to be introduced in the expression for the group velocity, in the refraction Equation (4), and in the form of the source function.

The source function for the deep water case may be represented as a superposition of the wind input – S_{in}, nonlinear transfer – S_{nl}, and white capping dissipation source function – S_{dis}:

$$S=S_{\mathrm{in}}+S_{\mathrm{nl}}+S_{\mathrm{dis}}. \quad (7)$$

To generalize the deep-water transport equation (1) to shallow water, the source function (7) needs to be extended to include an additional source function S_{bf} representing the energy loss due to bottom friction and percolation. The other terms of the transport equation must also be suitably modified to allow for the dependence on the depth D of the finite depth dispersion relation.

$$\omega=(gk\tanh(kD))^{1/2}. \quad (8)$$

Specifically, the following changes were made:

- the additional bottom friction term was taken from the JONSWAP study [*Hasselmann et al.*, 1973]

$$S_{bf}=-\frac{\Gamma}{g^2}\frac{\omega^2}{\sinh^2(kD)}F, \quad (9)$$

with Γ = constant = 0.038 $\mathrm{m^2\,s^{-3}}$;

- the infinite depth group velocity $v=\frac{1}{2}\omega/k$ in the propagation equations (2)–(4) was replaced by the corresponding expression for finite depth D:

$$v=\frac{\partial\omega}{\partial k}=\frac{1}{2}\left(\frac{g}{k}\tanh(kD)\right)^{1/2}\left(1+\frac{2kD}{\sinh(kD)}\right); \quad (10)$$

- refraction due to variations of the water depth:

$$\dot{\theta}_D=\frac{1}{kR}\frac{\partial\omega}{\partial D}\left(\sin\theta\frac{\partial D}{\partial\phi}-\frac{\cos\theta}{\cos\phi}\frac{\partial D}{\partial\lambda}\right). \quad (11)$$

The model contains 25 frequency bands on a logarithmic scale with $\Delta f/f$ = 0.1, spanning a frequency range $f_{\max}/f_{\min}$ = 9.8 and 12 directional bands (30° resolutions). The frequency units can be selected arbitrarily. In all hind cast studies, the frequency interval extended from 0.042 to 0.41 Hz. Output data in six hourly intervals from 1979 to 2021 with resolution of 0.25°×0.25° were done.

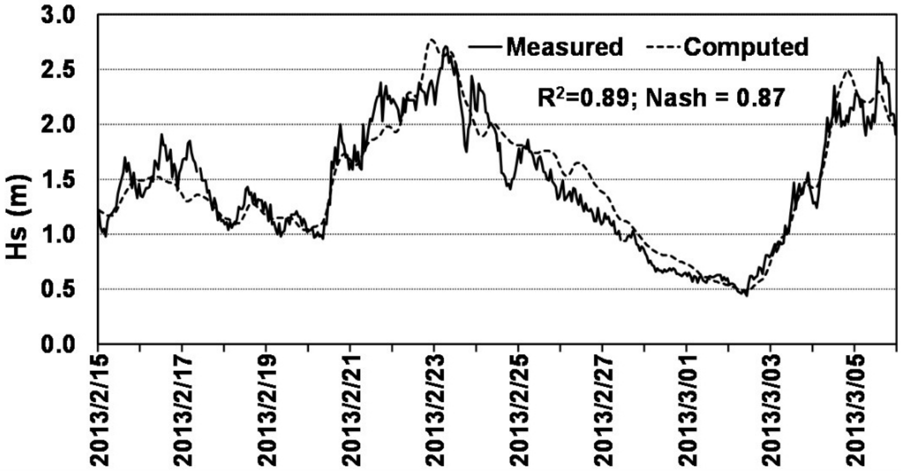

Figure 2: Comparison of measured and computed wave heights at Ninh Thuan station.

Table 1: Feature of study locations along Vietnam coast

No.	Locations	Longitude (°E)	Latitude (°N)	Depth (m)
1	Bach Long Vi Island	107.625	20.125	28
2	Con Co Island	107.375	17.125	45
3	Ly Son Island	109.125	15.375	58
4	Off Nha Trang coast	109.625	12.125	140
5	Phu Quy Island	108.875	10.375	54
6	Con Dao Island	106.625	8.625	29
7	Tho Chu Island	103.375	9.125	44

Verification of modelled results

To verify of the modelled results, the measured wave characteristic off the Ninh Thuan province waters at location ($\phi = 11.437$°N, $\lambda = 109.025$°E, depth ≈20 m) from 0 h 15 February 2013 to 23 h 5 March 2013 by the AWAC wave recorder Figure 2 were collected. The results of the comparison between measured and modelled significant wave height data are shown in Figure 2. Verify results show $R^2 = 0.89$ and $N_{\text{ash}} = 0.87$. Since the measured station is located in nearshore and shallow region, therefore, the measured one was affected by the topography condition.

The measured data from 0 h 15 February 2013 to 23 h 5 March 2013 were selected because this time is the period of dominant incident wave direction from NE, which reduces the effect of morphological conditions. From the reasonable accuracy of the verified results, the WAM model can be used to estimate wave characteristics in the SCS in general and in Vietnamese waters in particular.

To study the regime of wave height in Vietnamese waters, seven typical locations along Vietnamese coast were selected to extract the wave data from the WAM model (see Figure 1). Feature of typical study locations are shown in Table 1.

Seven typical locations are representative for different Vietnamese coast sections with typical geographical conditions (Table 2). The computed wave data from 1 January 1979 to 31 December 2021 at each typical location were analyzed. The wave regime features in Vietnamese waters were obtained from statistics, which include wave height patterns in the SCS during monsoons. Also, long-term distribution features of wave height in the SCS and wave regime features at typical locations along the Vietnamese coast were obtained.

Results and Discussion

Results

Wave height pattern in the SCS during monsoons

In NE monsoon period: at 3 h 1 January 2021 wind field over the SCS was strong with $V \geq 10\,\mathrm{m\,s^{-1}}$. In the areas of central and northeast was $V \approx 15$–$16\,\mathrm{m\,s^{-1}}$, the central and southern Vietnamese coast – $V \approx 12$–$15\,\mathrm{m\,s^{-1}}$, the areas of the Gulf of Tonkin and the Gulf of Thailand – $V \approx 8$–$10\,\mathrm{m\,s^{-1}}$. Northeast (NE) wind direction was dominated. This wind field formed a wave field being characteristic of NE monsoon with relatively stable wave direction from NE. The Gulf of Tonkin

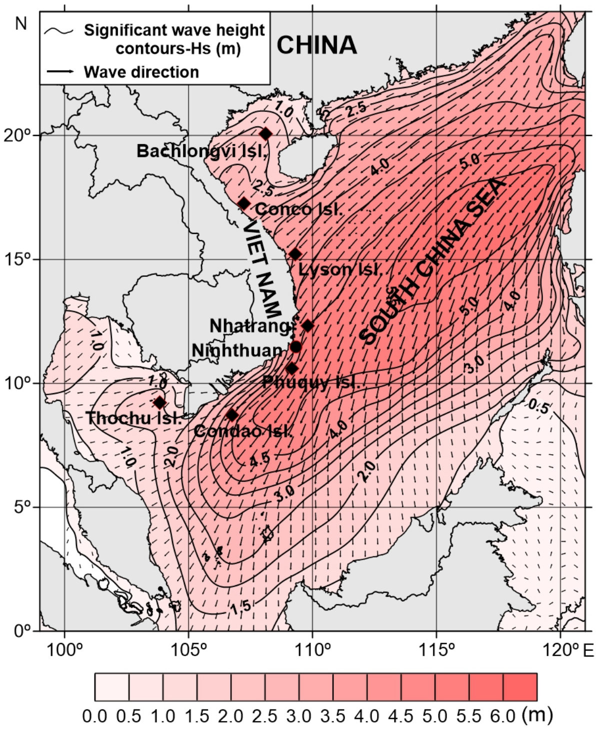

Figure 3: Wave height pattern over the South China Sea during NE monsoon (at 3 h 1 January 2021).

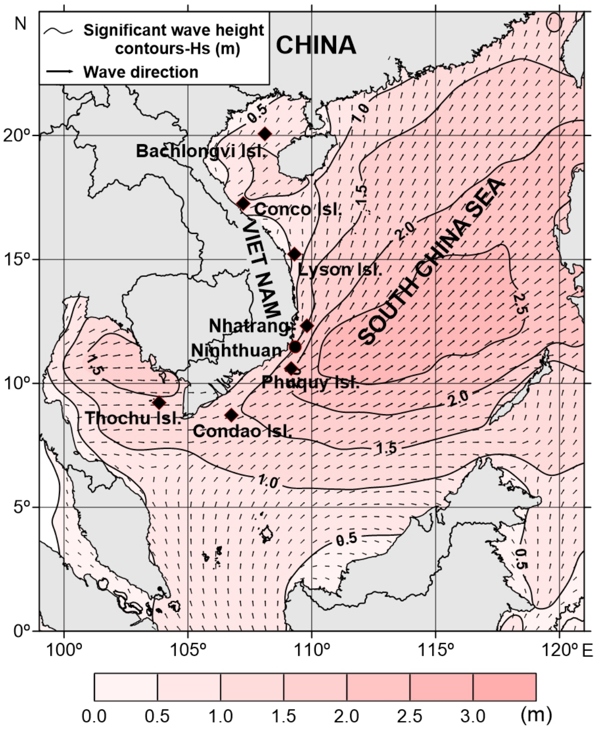

Figure 4: Wave height pattern over the South China Sea during SW monsoon (at 21 h 28 July 2021).

with H_s≈1–3 m (H_s – significant wave height is an average of 1/3 the largest of serial waves relative to average seawater level); the Gulf of Thailand with H_s≈1–2 m The central region of SCS was dominated by wind wave with H_s≈4–5 m (H_s – maximum significant wave height), wind wave of H_s≈3–4 m was close to the central Vietnamese coast (Figure 3).

In SW monsoon period, at 21 h 28 July 2021 wind field over SCS with $V \geq 6$ m/s was dominated; $V \geq 12$ m/s covered the central region of the SCS; central Vietnamese coasts with V≈8–10 m/s; the Gulf of Tonkin and Thailand with V≈8–10 m/s This season, the wind field over SCS in the Southwest (SW) direction was dominated. This wind field induced in the wave field being characteristic of SW monsoon with relatively stable wave direction from SW. In general, in the SW monsoon period, the SCS was dominated by a wave field with H_s≈1–2.5 m. The central region of SCS was dominated by a wave field with H_s≈2–2.5 m. The significant wave height contour of H_s≈1.5 m was close to the central Vietnamese coast. The Gulf of Tonkin and Thailand have H_s<1 m (Figure 4).

Long term distribution features of wave height in SCS

Statistical data of output wave characteristics from the WAM model for the period 1979–2021 show frequency distribution (%) of significant wave height H_s >1.0 m greater than 50% covering the northeast, central region of the SCS and central

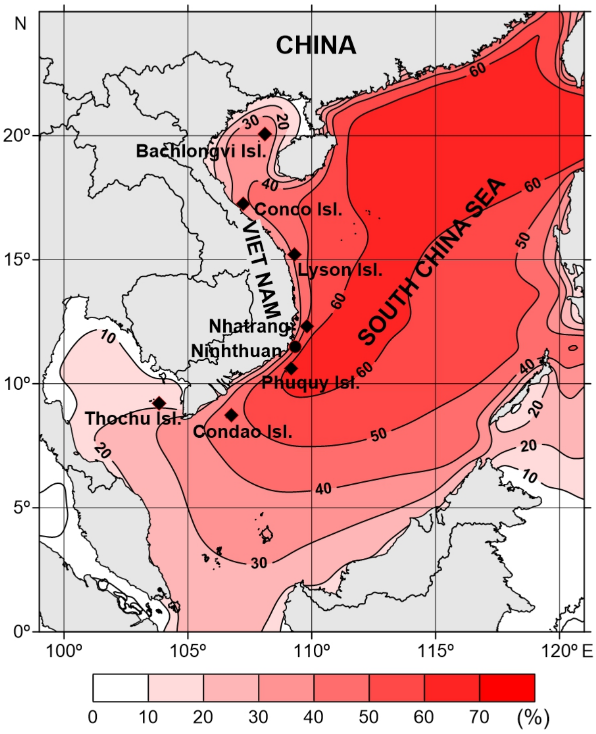

Figure 5: Frequency distribution of occurrence (%) in the case significant wave height H_s>1 m during 1979–2021.

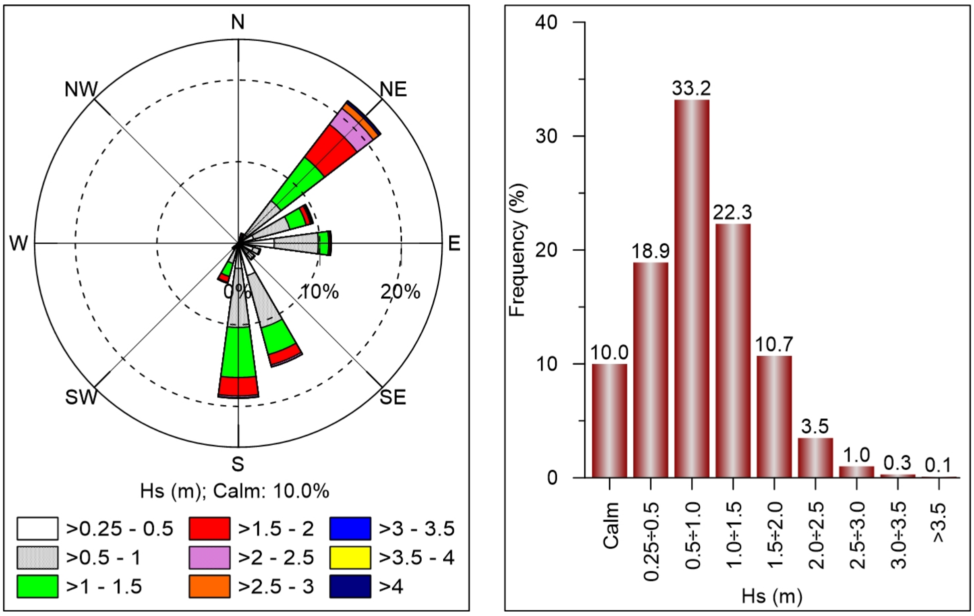

Figure 6: Wave rose diagram and frequency distribution of occurrence of significant wave height in Bach Long Vi Island region during 1979–2021.

Vietnamese coast. The area of the Gulf of Tonkin has frequency <40% and the Gulf of Thailand has frequency <30% (Figure 5).

Wave regime features at typical locations along Vietnamese coast

Statistical data of computed significant wave height for the period 1979 to 2021 at seven typical locations along the Vietnamese coast are presented in Table 2.

Table 2 shows the following.

1 – Bach Long Vi Island.

The Island is located in the Gulf of Tonkin and representative of the wave regime for northern Vietnamese waters (see Figure 1). The statistical data show that main wave directions were in NE, S, SSE with 22%, 18.9% and 15.6% respectively. The dominated wave height was H_s≈0.5–1.0 m with occurring frequency occupied of 33.2%, maximum wave height H_s>3.5 m occupied 0.1%. The wave height during the NE monsoon period was greater than that of the SW monsoon period (Figure 6). Bach Long Vi Island location has a short incident wave fetch during NE monsoon period, whereas it has a longer incident wave fetch during SW monsoon period. However, the incident wave energy during SW monsoon period underwent the refraction process by morphology conditions. The dominated SW incident wave direction in open sea was refracted to SSE direction in the island area.

2 – Con Co Island.

This location is representative of the northern central Vietnamese coast (see Figure 1). The statistical data of the WAM model show the dominated wave directions were in E, ESE, ENE with 27%, 21% and 19.9% respectively. The dominated wave height is H_s≈0.5–1.0 m occupied by 34.9%, maximum wave height of H_s>3.5 m occupied at 0.6%. The wave height during the NE monsoon period was greater than that of the SW monsoon period (Figure 7).

Data from Figure 6 and Figure 7 indicate the shifting of dominated wave direction in NE at Bach Long Vi Island to E direction at Con Co Island. That is, the dominated wave direction was from E not from NE, which indicating the influence of Hainan Island on incident wave active fetch. In addition, the Con Co Island is stronger due to the effect of incident wave energy from the open sea. This incident wave underwent the refracted process by Hainan Island during NE monsoon period.

3 – Ly Son Island.

The Island is representative of the central Vietnamese coast (see Figure 1). The statistical data show that dominated wave directions were in ENE, NE, SE, SSE with 32.8%, 17.4%, 16.5% and 13.8% respectively. The dominated wave height is H_s≈0.5–1.0 m occupied by 39%, maximum wave height of H_s>3.5 m occupied at 1.5% Figure 8. During the SW monsoon period the dominated wave directions were in SE, SSE, not in SW. This phenomenon shows the effect of morphology. That is the laying direction of the central Vietnamese coastline, which was approximately N–S axis. Therefore, at Ly Son Island area, the dominated incident wave was in ENE direction.

4 – Off Nha Trang coast.

Offshore region of Nha Trang city is a region of narrow continent with a depth contour of 200 m

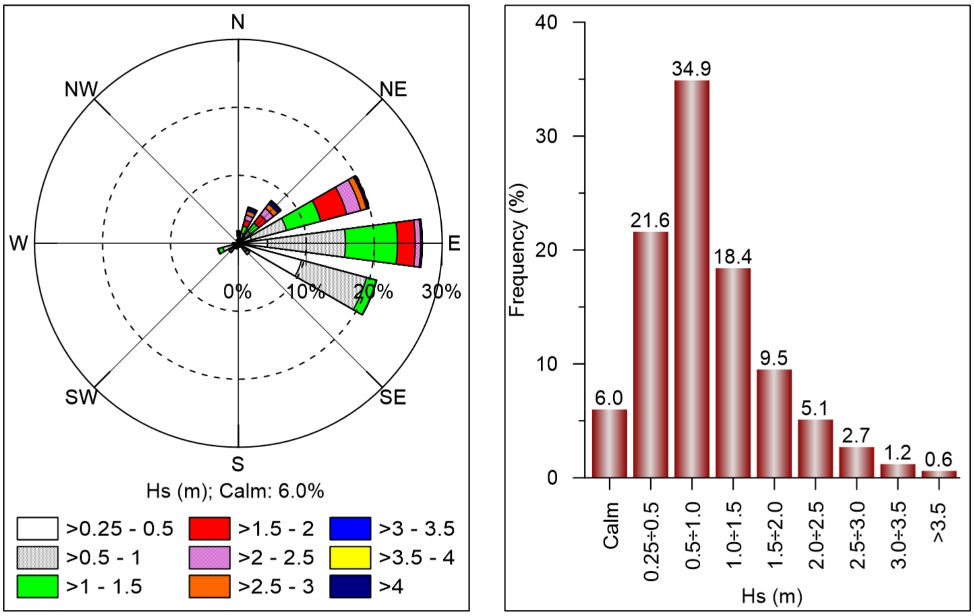

Figure 7: Wave rose diagram and frequency distribution of occurrence of significant wave height in Con Co Island region during 1979–2021.

Table 2: Wave regime characteristics at study locations along Vietnamese coast

No.	Locations	Representative	Occurring frequency of dominant wave directions (%)	Occurring frequency of dominant significant wave height $H_s \approx 0.5–1.0$ m (%)	Occurring frequency of maximum significant wave height $H_s > 3.5$ m (%)
1	Bach Long Vi Island	Northern Viet Nam coast (the Gulf of Tonkin)	NE / 22.0 S / 18.9 SSE / 15.6	33.2	0.1
2	Con Co Island	Northern Central Vietnamese coast	E / 27.0 ESE / 21 ENE / 19.9	34.9	0.6
3	Ly Son Island	Central Vietnamese coast	ENE / 32.8 NE / 17.4 SE / 16.5 SSE / 13.8	39.0	1.5
4	Off Nha Trang coast	South Central Vietnamese coast	NE / 32.4 SSW / 23.9 NNE / 13.3	35.6	2.6
5	Phu Quy Island	Southernmost of Central Vietnamese coast	NE / 43.7 WSW / 18.0 SW / 14.0	23.6	3.1
6	Con Dao Island	Southern Vietnamese coast	ENE / 45.0 WSW / 14.0	32.3	1.1
7	Tho Chu Island	The Gulf of Thailand	ESE / 29.1 W / 10.7 E / 10.2	39.1	0

close to the coastline. Therefore, this area was strongly affected by wave action, especially during NE monsoon period. This location is representative of the south-central Vietnamese coast (see Figure 1). The statistical data show that main wave directions were in NE, SSW, and NNE with 32.4%, 23.9% and 13.3% respectively. The dominated wave height is $H_s \approx 0.5–1.0$ m occupied at

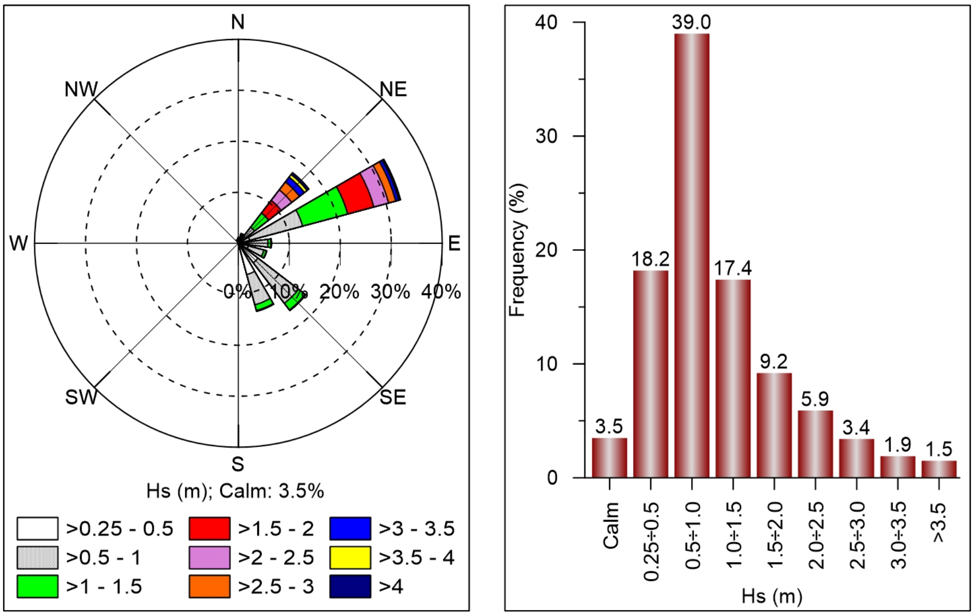

Figure 8: Wave rose diagram and frequency distribution of occurrence of significant wave height in Ly Son Island region during 1979–2021.

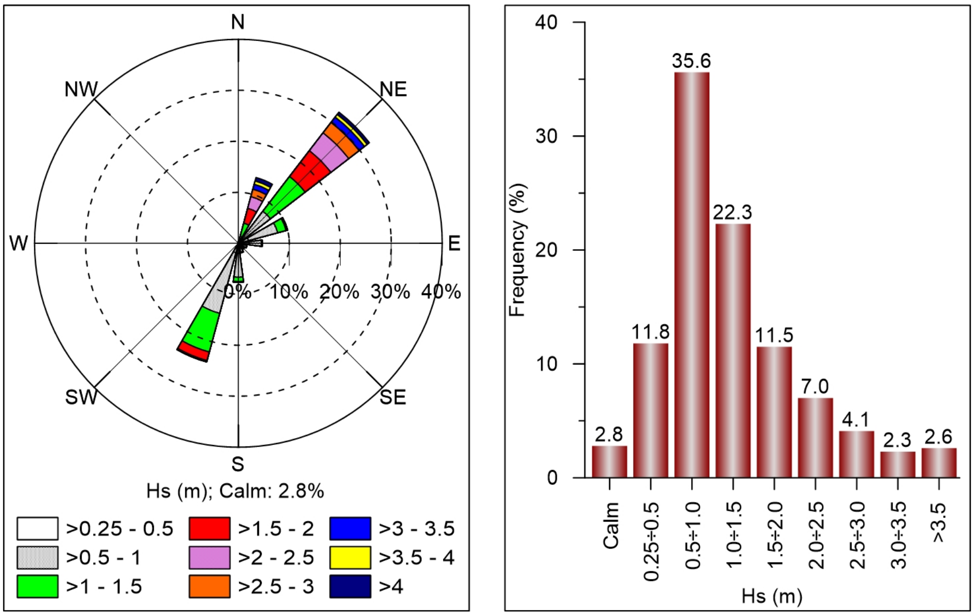

Figure 9: Wave rose diagram and frequency distribution of occurrence of significant wave height off Nha Trang coast region during 1979–2021.

36.6%, maximum wave height of H_s>3.5 m occupied at 2.6% (Figure 9).

In comparison to the Ly Son Island area, Nha Trang area is influenced stronger by wave action during the SW monsoon period, which indicates the occurring frequency of the incident SSW wave direction (23.9%).

5 – Phu Quy Island.

The Island is located in the offshore region of Binh Thuan province coast (approximately 80 km from the coast). Therefore, this area is strong affected by wave action during both seasons (NE and SW monsoons), the island is representative of the southernmost area of the central Vietnamese coast (Figure 1). The statistical data show that main wave directions were in NE, WSW, and SW with 43.7%, 18.0% and 14.0% respectively. The dominated wave heights are H_s≈0.5–1.0 m occupied at 23.6% and H_s≈1.0–1.5 m occupied at 22.4%, maximum wave height H_s>3.5 m occupied at 3.1% (Figure 10). However, during the NE monsoon period, the island area was influenced stronger by wave action in comparison with the SW monsoon period. Since the wind intensity, water depth and wave fetch for SW incident wave direction were less than in comparison with NE incident wave direction.

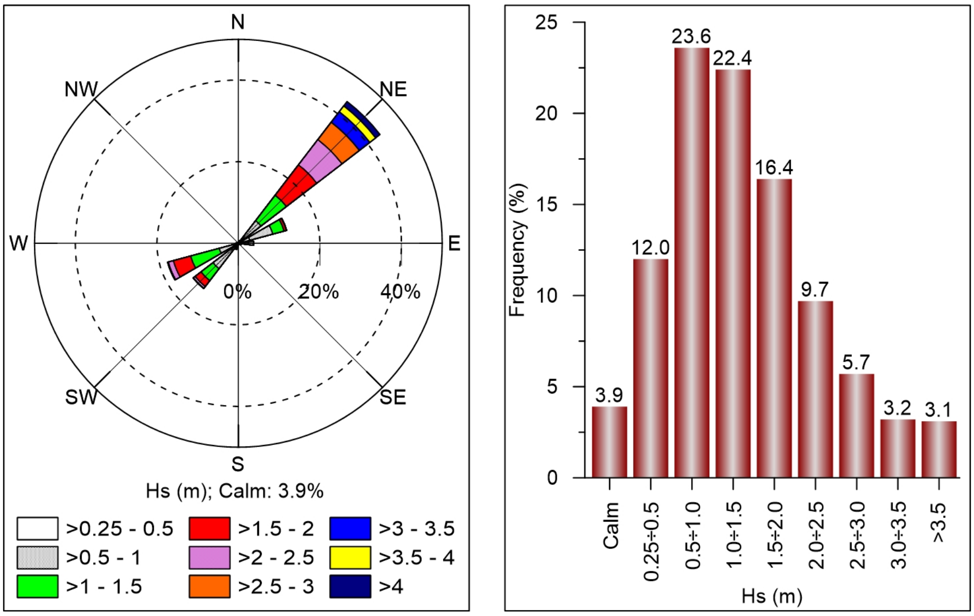

Figure 10: Wave rose diagram and frequency distribution of occurrence of significant wave height in Phu Quy Island region during 1979–2021.

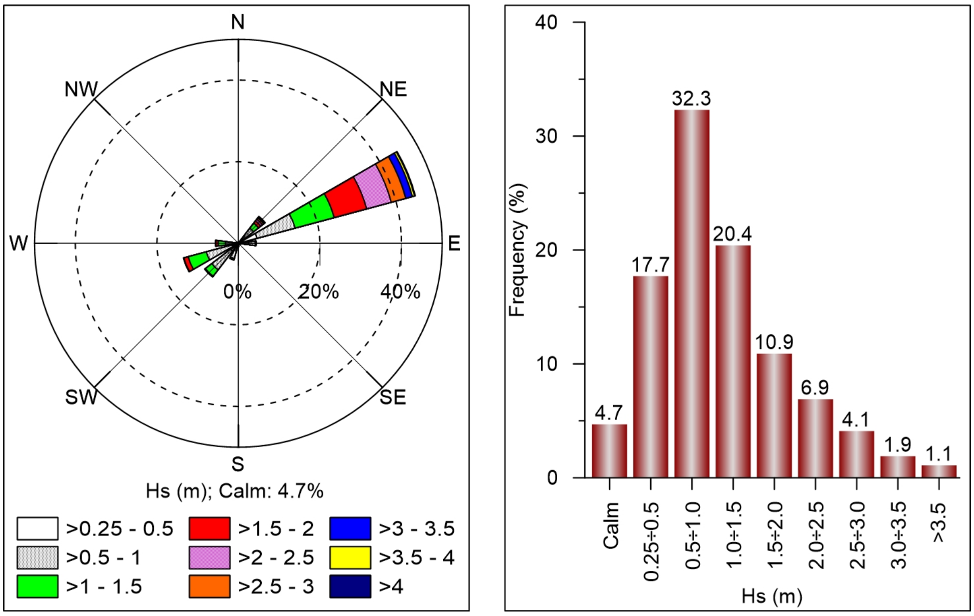

Figure 11: Wave rose diagram and frequency distribution of occurrence of significant wave height in Con Dao Island region during 1979–2021.

6 – Con Dao Island.

The Island is located in the offshore region of the Mekong River delta coast (approximately 80 km from the coast), and it is a shallow water region (water depth less than 50 m). This area is affected by wave action during both seasons (NE and SW monsoons) and the island is representative of the southern Vietnamese coast (see Figure 1). The statistical data show that dominated wave directions were in ENE and WSW with 45.0% and 14.0% of occurrence respectively. The dominated wave height is H_s≈0.5–1.0 m occupied at 32.3%, maximum wave height H_s>3.5 m occupied at 1.1% (Figure 11). During the NE monsoon period, the island area was influenced stronger by wave action in comparison with the SW monsoon period. Because, the wind intensity, water depth and wave fetch of NE incident wave were larger than that of SW incident wave direction.

7 – Tho Chu Island.

The Island is located in the offshore region of Ca Mau-Kien Giang province's coast (approximately 145 km from the coast). Therefore, this area is less affected by wave action during both seasons (NE and SW monsoons) and the island is representative of the wave regime in the Gulf of Thai-

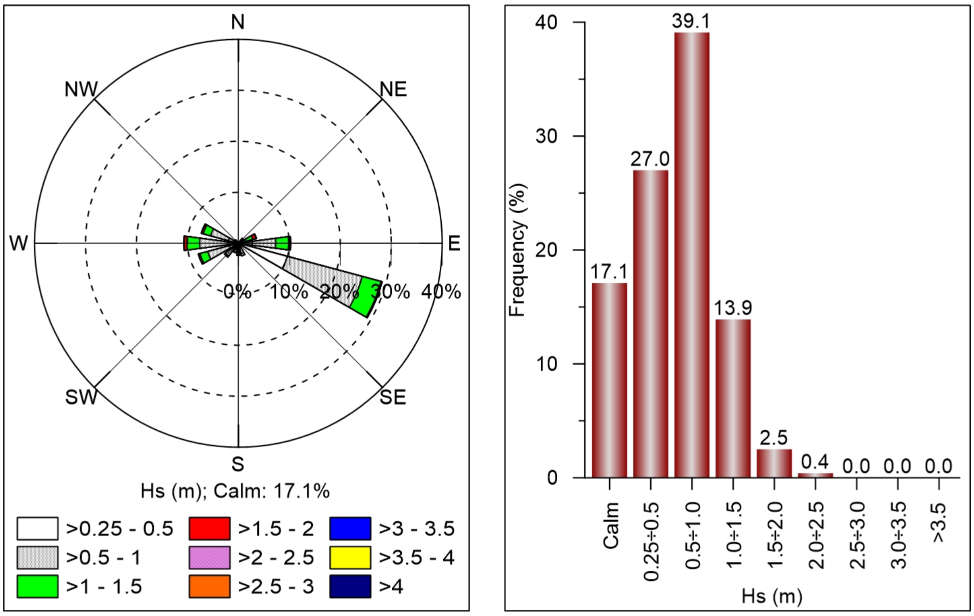

Figure 12: Wave rose diagram and frequency distribution of occurrence of significant wave height in Tho Chu Island region during 1979–2021.

land (see Figure 1). The statistical data show that the dominated wave directions were in ESE, W and E with 29.1%, 10.7% and 10.2% of occurrence respectively. The dominated wave height is H_s≈0.5–1.0 m occupied at 39.1%, maximum wave height H_s>3.5 m occupied at 0% (Figure 12). The location condition shows the island area was influenced stronger by wave action from the open sea.

The Table 2 shows the summary of the main wave regime features at seven typical locations. The data show that the NE monsoon wave was more prevailing and stronger than that of the SW monsoon wave. The occurring frequency number of maximum significant wave height H_s>3.5 m in the Central Vietnamese coast from Ly Son Island to Phu Quy Island was higher than 1.5% that was the strongest effect area by wave action. However, the figures of maximum significant wave height in the Gulf of Tonkin (Bach Long Vi Island) and the Gulf of Thailand (Tho Chu Island), which had less effect by wave action, were lower than 0.1%. Wave action impacted two islands: Con Dao and Phu Quy, during both seasons, with these figures were at 3.1% and 1.1% respectively.

Discussions

Vietnam has a long coastline of 3200 km and many islands and a large population lives along the coast and the marine economy plays an important role for the country's development. Therefore, estimation of the wave regime of Vietnamese waters has a significant impact on marine economic sustainable development such as maritime, fishing, mariculture, tourism, design of hydro-structures, environment protection etc.

WAM model is a third-generation wave model which permits to simulate the progress of wave spectrums especially in case of typhoons, fronts when wind field changes significantly in both directions and speeds. The model runs for any given regional or global grid with a prescribed topographic dataset. Therefore, this paper using the WAM cycle 4.5 with model domain covered the SCS with a resolution of $\Delta X = \Delta Y = 0.25°$ and modern input data set for the period 1979–2021 to estimate wave parameters in Vietnamese waters was a reasonable method. And the result of model verification showed a good agreement between measured and modelled ones. The extracted wave parameters from the WAM model will be open boundary data for nearshore wave models [*Booij et al.*, 1999] especially for estimation of the design wave parameters [*SPM*, 1984]. From the studied results of this paper, it is necessary to carry out a study to get the wave regime for different Vietnamese coast sections. This work was conducted in developed countries, such as in the USA [*SPM*, 1984].

The SCS connects to the adjacent seas through many straits. The model domain was used to direct the problem into being, that is how to estimate the incident wave parameters at open boundaries especially along Luzon Strait where incident waves penetrate into the SCS from western Pacific Ocean. To solve this problem, the needs are extending the model domain and enhancing the computing system.

Up to this time, almost all of longtime observed wave data (less than one year duration) were carried out by the scientific contracts between the Institute of Oceanography and private companies. Meanwhile, almost all national scientific programs on longtime observed wave data are still lacking. *Le et al.* [2015] showed that at present, ocean observations and services levels in Vietnam still have shortcomings in both manpower and equipment and mostly for the nearshore region. Public access to oceanographic data was still limited and not in professional. Therefore, observed data do not satisfy the demand of scientists to forecast oceanographic processes, especially for dangerous disaster conditions such as storms, flood.

From 2009 the Center for Oceanography, Vietnam has installed equipment to measure wave and current by radar high frequency system 4.3–5.4 MHz at three stations at Quang Binh, Ha Tinh and Hai Phong Provinces (the Gulf of Tonkin). The specification of Hai Phong radar station is the range of surface current measurement is 200 km, range of wave measurement is above 20 km. Ha Tinh and Quang Binh radar stations specification are the range of surface current measurement is above 300 km, range of wave measurement is above 20 km. The data are transferred each hour (24 /24 h) in a day from these stations to central station in Hanoi through high-speed internet (ADSL). Up to now, these radar stations have started running and initially have collected data of sea surface state such as wave and current serving for the development of economy and society in Tonkin Gulf.

We must obtain the better accuracy of wave regime characteristics at each section along Vietnamese coast. The necessary works are enhancing the capacity in the ocean observation and forecasting, which including enhance the ocean observations and services by means of upgrades of manpower on oceanography and by international cooperation in training program. In addition, we must equip more modern observe and analysis instruments including vessel, mooring station system and computer capacity for marine investigation in the open sea; enhance of exchange information on oceanographic data between different institutions including internationally; enhance of public access on oceanographic data; enhance the ocean observation and forecast capacity.

Le and Nguyen [2018] based on the longtime observation of wave parameters off Ninh Thuan province coast show that during 2013 the dominant wave directions were in ENE, E, SSE and SE with occurring frequencies of 36.7%, 20.5%, 18.2% and 11.6% respectively. During the NE monsoon period (November, December, January, February) the dominated wave directions were in ENE and E. During the SW monsoon period (June, July, August) the dominated wave directions were in SSE and SE. The duration and intensity of wave action were dominated in the NE monsoon and typhoon activity period. These data are good agreement with modelled wave regime characteristics of this study for Khanh Hoa – Ninh Thuan provinces waters.

The observed wave data for verify of the modelled results were collected at location with depth ≈20 m. It is the nearshore shallow water. But the time from 0 h 15 February 2013 to 23 h 5 March 2013 is the period of dominant incident wave direction from NE which reduce the effect of morphological condition to the modelled results. Therefore, it is reasonable evidence to apply the WAM model to estimate the wave regime in Vietnamese waters.

The main modelled data on wave regime characteristics along Vietnamese coast from this study showed occurring frequency (%) H_s>1.0 m during 1979 to 2021. These study results are the initial basic scientific for marine economic sustainable development of Vietnam. At present, Institute of Oceanography, Vietnam Academy of Science and Technology (IO VAST) and Korea Institute of Ocean Science and Technology (KIOST) have joined the international project on: "Capacity Building on Operational Oceanography in Vietnam". The main objective of this project is to develop an integrated Vietnamese operational oceanographic system (VOOS) that provides broadcasts and forecasts of ocean information around Vietnam to support marine activities and to mitigate coastal disasters. In the future, Vietnam has to modernize its ocean observation and forecasting capacity. This problem could be solved in the framework of IOC/WESTPACT program.

Conclusions

In Vietnamese waters, NE monsoon waves affected from October to April of the next year, SW monsoon waves affected from June to August. May and September are transitional periods. During the NE monsoon, the main wave direction was NE and vice versa during the SW monsoon. The NE monsoon wave was dominant and stronger than that of the SW monsoon wave.

Occurrence frequency significant wave height (%) H_s>1.0 m during 1979 to 2021 was greater than 50% in the northeast, central region of SCS, and central Vietnamese coast. The Gulf of Tonkin and the Gulf of Thailand have frequencies <40% and <30% respectively.

The central Vietnamese coast from Ly Son to Phu Quy Islands was the most influenced by wave action, where the occurring frequency of maximum significant wave height (H_s>3.5 m) was greater than 1.5%. The area of the Gulf of Tonkin (Bach Long Vi Island) and the Gulf of Thailand (Tho Chu Island) were less affected by wave action, where the occurrence frequency of maximum significant wave height (H_s>3.5 m) was less than 0.1%. Phu Quy and Con Dao Islands were strong affected by wave action during both seasons.

The WAM model and the assimilation of wind data at high resolution $\Delta X = \Delta Y = 0.25°$ permit to get the wave regime features in the Vietnam waters with reasonable accuracy.

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