

APPLICATION OF SWAN MODEL FOR HINDCASTING WAVE HEIGHT IN JEPARA COASTAL WATERS, NORTH JAVA, INDONESIA

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ABSTRACT: SWAN (Simulating Wave Near-shore) is a numerical wave model for hindcasting/forecasting wave parameters in coastal areas. This numerical model is chosen because is suitable for shallow water. This study was conducted to verify the results of wave height hindcasting in Jepara coastal waters. This is expected to support wave characteristic research based on wave forecasting for 10 years in the waters between Java, Sumatera and Kalimantan. The model is run with the third-generation mode (GEN3), which allow wind input, quadruplet and triad interactions, whitecapping, and breaking. Wind data is obtained from ECMWF (European Centre for Medium-Range Weather Forecasts) and the bathymetry from GEBCO (General Bathymetric Chart of The Oceans). The validation of the model and buoy data during July - December 1993 shows a good result (Root Mean Square Error = 0.166 and correlation/ linear regression = 0.807). Based on the literature, qualitatively the model has been verified with other simulation from another model in the same location.

Keywords: SWAN Model, Hindcasting, Jepara Coastal Waters, Significant Wave Height, Validation

1. INTRODUCTION

Considering the difficulty to obtain waveform measurement data in Indonesia, wind wave hindcasting was often used in onshore and offshore building planning. There is a significant difference between measurement results and forecasting [1], so it needs to be verified with the measurement results.

The purpose of this study is to find whether the SWAN set up give results in accordance with the measurement results in Jepara coastal waters. This study was conducted to support the research of wave characteristics based on wave forecasting for 10 years in the waters between Java, Sumatera and Kalimantan using SWAN model from TU Delft (Delft University of Technology).

SWAN (Simulating Wave Near-shore) is a numerical wave model for hindcasting wave parameters in coastal areas. This numerical model was chosen because the reference is suitable for shallow water. Shallow water has many nonlinear factors that affect the wave greatly. In addition, this model can be accessed directly without the need to pay licenses and has been used widely by researchers in various countries. SWAN is now a viable option for operational high-resolution nonstationary wave predictions at sub-regional scale [2]. It is relatively quick to set up and user-friendly in operation, but some terms should be improved and not all interactions are included (e.g.

bottom friction). It is expensive in terms of computer time. Running long time series on a PC is prohibitive [3]. Besides that, the difference in density gives very significance effect to the relative wave amplitude [4].

This research is concerned the development of a methodology for nesting from ocean to local scale using SWAN, where waves are first simulated for a larger area using a coarse grid and then downscaled to a finer grid covering a smaller area. The boundary conditions for the finer grid are derived from the coarse grid computation. There are several nesting techniques that can be implemented to produce a high-resolution local scale model. One common difference in techniques is the source of the boundary data for the coarse model. The most holistic approach is to nest from a global domain to a regional/sub-oceanic domain and, lastly, to a local coastal domain [5].

Gorman et.al [6] show the simulations were validated using data from an inshore site in 30 m water depth at Mangawhai on the north-east coast of the North Island. Use of the nested model improved the agreement between model and measured significant wave height, decreasing the scatter index from 0.50 to 0.26. The suite of tools provided by the hindcast and localized, shallow water models can provide accurate new wave information for most of New Zealand's coastline.

2. PHYSICAL PROCESSES

All information about the sea surface is contained in the wave variance spectrum or energy density $E(\sigma, \theta)$, distributing wave energy over (radian) frequencies σ (as observed in a frame of reference moving with current velocity) and propagation directions θ (the direction normal to the wave crest of each spectral component). Usually, wave models determine the evolution of the action density $N(x, t; \sigma, \theta)$ in space x and time t . The action density is defined as $N = E/\sigma$ and is conserved during propagation in the presence of ambient current, whereas energy density E is not. It is assumed that the ambient current is uniform with respect to the vertical co-ordinate and is denoted as U [7].

The evolution of the action density N is governed by the action balance equation, which reads [8]:

$$\frac{\partial N}{\partial t} + \nabla_x [(c_g + U)N] + \frac{\partial c_{\sigma} N}{\partial \sigma} + \frac{\partial c_{\theta} N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

The left-hand side is the kinematic part of this equation. The second term denotes the propagation of wave energy in two-dimensional geographical x -space, with the group velocity $c_g = \partial \sigma / \partial k$ following from the dispersion relation $\sigma^2 = g|k| \tanh(|k|d)$ where k is the wave number vector and d the water depth. The third term represents the effect of shifting of the radian frequency due to variations in depth and mean currents. The fourth term represents depth-induced and current-induced refraction. The quantities c_{σ} and c_{θ} are the propagation velocities in spectral space (σ, θ) . The right-hand side contains S_{tot} , which is the source/sink term that represents all physical processes which generate, dissipate, or redistribute wave energy. They are defined for energy density $E(\sigma, \theta)$. The second term in Eq. (1) can be recast in Cartesian, spherical or curvilinear co-ordinates. For small-scale applications, the spectral action balance equation may be expressed in Cartesian co-ordinates as given by [7]

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_{\sigma} N}{\partial \sigma} + \frac{\partial c_{\theta} N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (2)$$

with

$$c_x = c_{g,x} + U_x, \quad c_y = c_{g,y} + U_y \quad (3)$$

With respect to applications at shelf sea or oceanic scales the action balance equation may be recast in spherical co-ordinates as follows [7]:

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_{\sigma} N}{\partial \sigma} + \frac{\partial c_{\theta} N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (4)$$

with longitude λ and latitude ϕ [7].

In shallow water, six processes contribute to S_{tot} :

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (5)$$

These terms denote, respectively, wave growth by the wind, nonlinear transfer of wave energy through three-wave and four-wave interactions and wave decay due to whitecapping, bottom friction and depth-induced wave breaking [7].

There are some options in SWAN regarding the model set-up which pertains to the type and/or parameterization of the formulations used for the source terms in Eq.(5). The user can choose between three different formulations for S_{in} , which accounts for the linear and exponential growth of waves due to wind [5].

Wind energy to waves is commonly described as the sum of linear and exponential growth. There are two wind growth models in SWAN that are available for us. Both expressions of wind growth model of them share the following form (Eq.(6)) and the same linear growth (Eq.(7)), while the exponential growth term is different.

$$S_{in}(\sigma, \theta) = A + BxE(\sigma, \theta) \quad (6)$$

In which A describes linear growth and BxE exponential growth [9].

Linear growth by wind:

$$A = \frac{\alpha}{g^2 2\pi} [U_* \max(0, \cos(\theta - \theta_w))]^4 H \quad (7)$$

with

$$H = \exp(-(\sigma/\sigma_{PM}^*)^4) \quad \text{and} \quad \sigma_{PM}^* = \frac{0.13g}{28U_*} 2\pi \quad (8)$$

Exponential growth:

a. Expression from [10]:

$$B = \max[0, 0.25 \frac{\rho_a}{\rho_w} \left(28 \frac{U_*}{C_{ph}} \cos(\theta - \theta_w) - 1 \right)] \sigma \quad (9)$$

in which U_* is friction velocity, θ_w is wind direction, C_{ph} is the phase speed and ρ_a and ρ_w are the density of air and water, respectively.

b. Expression from [11]:

$$B = \beta \frac{\rho_a}{\rho_w} \left(\frac{U_*}{C_{ph}} \right)^2 (\max(0, \cos(\theta - \theta_w)))^2 \sigma \quad (10)$$

where β is the Miles“constant”.

The dissipation term of wave energy is represented by the summation of three different contributions: white-capping $S_{ds,w}$, bottom friction $S_{ds,b}$ and depth-induced breaking $S_{ds,br}$ [7].

3. MATERIALS AND METHODS

3.1 Available Data

The scarcity of time series oceanographic datasets, especially the observational wave data, is one of the challenges to develop the ocean model in Indonesia. However, data is obtained from long-term wave observation located in Jepara, Central Java (110.7722°E, 6.3983°S), which has granted the access from PT. Geomarindex. The data is from July to December 1993 with three-hour temporal resolution. The available parameter is only the wave height values.

The bathymetry data is obtained from General Bathymetric Chart of the Oceans (GEBCO) with a spatial resolution of 30 arc-sec (~1 km). There is no available local bathymetry dataset to cover the coastal waters. Therefore, it is applied to all model domains. The only forcing included in this wave model is from the wind. It is obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.125 degrees (~13.75 km) and 6-hour temporal resolution. The FNMOC global WW3 model is vastly used for open boundary condition of wave forcing in several studies, e.g. [5], however, wave data in 1993 is unavailable.

The significant wave height output from the ECMWF reanalysis (ERA)-Interim reanalysis is used as a comparison to our model. The nearest point to the buoy station is located at 110.75°E and 6.375°S. The distance between these two points is 4.16 km or 4 grid cells in the smallest domain.

3.2 Model Domain

The SWAN model provides nesting application to the parent grid. Hence, there is two model domains, the Java Sea (JS) domain as the parent grid and Jepara Coastal Waters (JCW) domain as the child/nested grid (Fig. 1). The JS domain extends from Aceh to Bali that includes two marginal seas, i.e. the South China Sea and the Java Sea, while the JCW domain covers the Jepara coastal waters

(110.450°E - 110.918°E and 5.996°S - 6.450°S). The JS and JCW domains have 1/8 degree and 1/96 grid resolutions with the total of 176x120 and 44x48 grid-cells, respectively.

The bathymetry in this region is relatively shallow (<100 m), with the presence of narrow straits (e.g. Malacca Strait) and small islands that add the complexity of the model domain (Fig. 1). The deep waters are concentrated in the edge of model domain, i.e. North of Sumatera (top-left), North of Kalimantan (top-right), and North of Bali (bottom-right). The depth range is 500-3300 m.

3.3 Model Setup

The non-stationary 2D wave model within SWAN is simulated with 1-hour interval from July to December 1993. The frequency range is set at 0.3-1.1 Hz and divided linearly into 38 frequencies. The number of directional bins is set for 72 due to the physical characteristics of the study areas, such as the geographical conditions, bathymetry gradients, and global and local wind effects [12]. In addition, the first order, backward space, backward time (BSBT) numerical scheme are employed for both model domains with three maximum number of iterations and 98% percentage of accuracy for the wet/dry condition.

The same physics setup is applied to both domains. GEN3 wave model with Komen linear growth formulation and the white capping default configurations were used [10]. Further, the triad and quad wave-wave interaction, as well as breaking and diffraction processes are activated by using the default configurations [7]. For bed friction, the dissipation coefficients (C_b) was 0.019 as suggested for the region with smooth sediment characteristic, while the default value was 0.038 [7]. The vegetation, turbulence, and fluid mud are omitted in the physical processes due to the absence of datasets. Finally, the model is simulated in parallel computing with OpenMP (Open Multi-Processing) to reduce computation times.

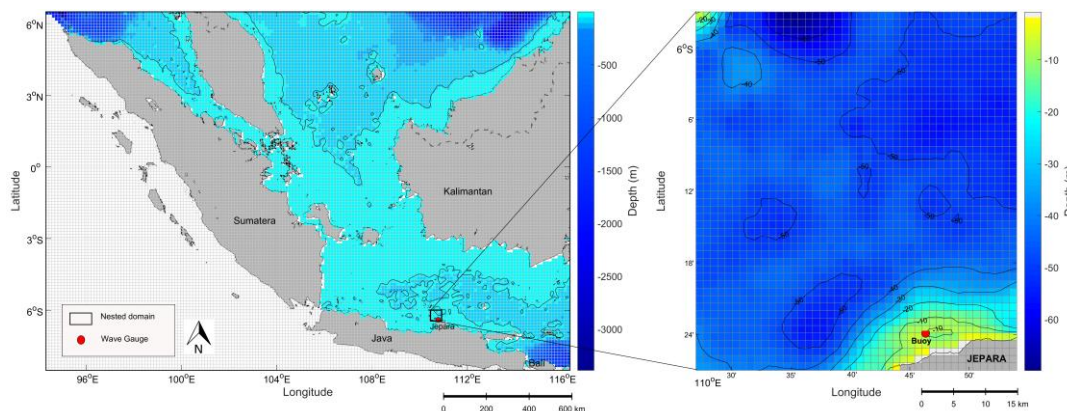


Fig.1 Grid-view of wave model domains; (left) JS domain with isobath at 50 m and (right) JCW domain with 10 m of isobath interval. Red point denotes a buoy location.

4. RESULTS AND DISCUSSION

4.1 Model Validation

Wave statistics for the buoy sites were computed from the hindcast. Occurrence statistics for significant wave height H_s , mean direction Q_{mem} , and second moment mean period T_{m2} were computed. Significant wave height results were compared with data over the relevant deployment periods.

Significant wave height at a wave buoy site as simulated by the wave model and as measured by the buoy, shown as time series in Fig.2a and regression in Fig.2c, with the line of best fit and equivalence lines shown by dashed and solid lines respectively.

In December 1993, there appeared to be extreme wave height (see Fig.2b) and after further study of the cause, this was due to Manny typhoon where propagation of waves from the center of the cyclone

Manny to Jepara occurred over 10 days (see Fig.2d).

The result of forecasting with SWAN shows a wave distribution pattern corresponding to the buoy data, except for the duration of Oct-Nov 1993 for which the wave height of the measurement needs to be reconfirmed.

Factors that may affect the inaccuracy of the model:

1. Coarse resolution of bathymetry dataset used in this model
2. Global wind data are usually unable to achieve the magnitude of extreme events
3. The absence of wave-current interaction in the model and static water level (zero value)
4. The grid on the model is also still rough and in rectangular form
5. The accuracy of the buoy data for validation also needs to be confirmed again, especially the Oct-Nov 1993 timeframe, because the wave height was only about 10-15 cm.

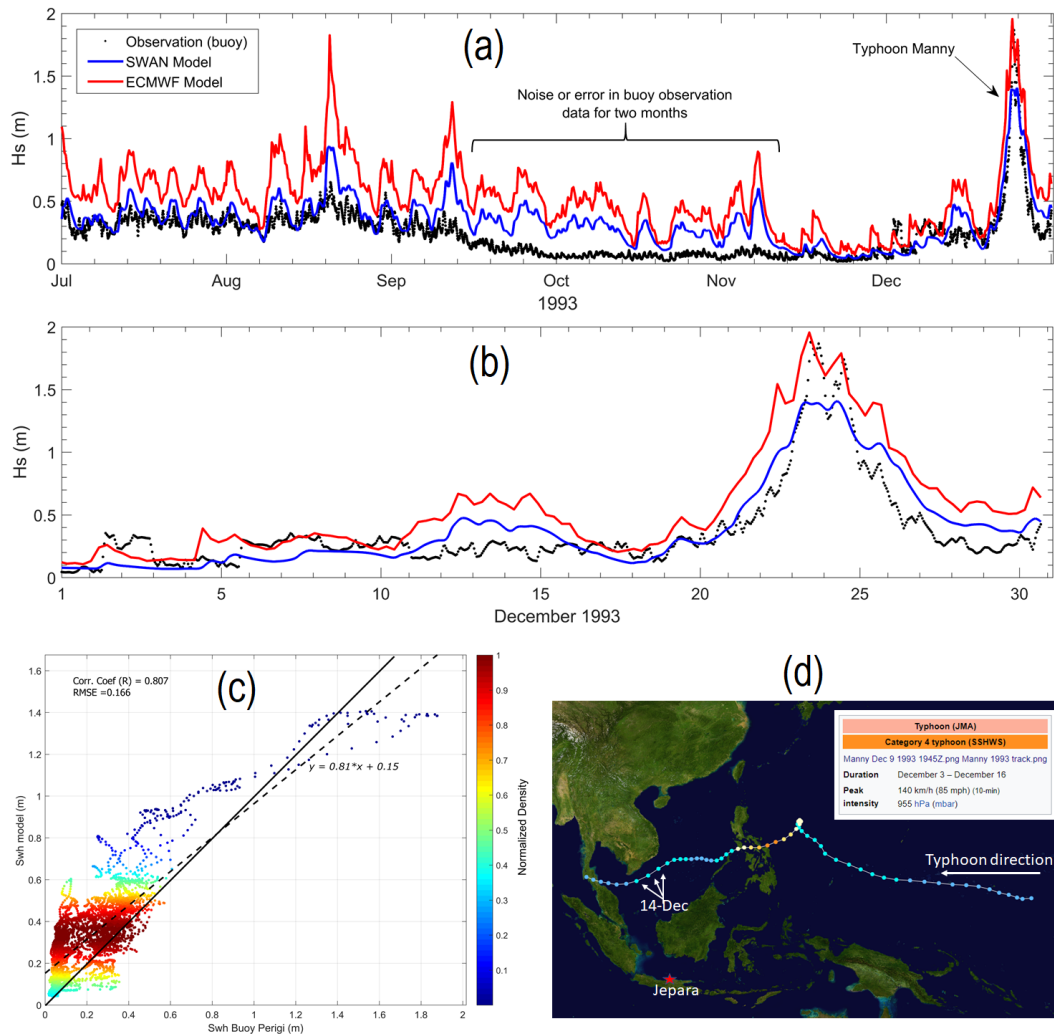


Fig.2 (a) and (b) are showing time-series of significant wave height from SWAN model (blue line), ECMWF model (red line) and buoy observation (black dots) for whole observation period and during Typhoon Manny, respectively. (c) H_s density plot of SWAN & Jepara Buoy, and (d) Typhoon Manny propagation track that obtained from Joint Typhoon Warning Center (JTWC) and plotted in Google Earth.

Table 1. Significant wave height (H_s) statistic in the Jepara Buoy station and the model accuracy. R is correlation coefficient and SI is scattered index.

Data	Basic Stats				Model Accuracy			
	Min	Max	Mean	Std	RMSE	R	Bias	SI
Jepara Buoy	0.017	1.878	0.230	0.202	x	x	x	x
SWAN	0.041	1.406	0.339	0.203	0.166	0.807	-0.109	0.720
ECMWF*	0.071	1.955	0.535	0.288	0.354	0.778	-0.304	1.535

* Significant wave height output from the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis (ERA)-Interim reanalysis

4.2 Comparison with Existing Models

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organization supported by 34 states. ECMWF is both a research institute and a 24/7 operational service, producing and disseminating numerical weather predictions to its Member States. This data is fully available to the national meteorological services in the Member States [13].

The result of SWAN modeling is compared with the wave forecasting result from ECMWF as shown in Fig 2a and 2b. Both models exhibit similar wave distribution patterns, although H_s ECMWF model results tend to be always larger than the H_s model of SWAN.

Statistical analysis for H_s model and H_s buoy included minimum, maximum, mean, standard deviation and model accuracy values against the measurement results are presented in Table 1 where the H_s model SWAN (0.807) showed a better correlation value than H_s ECMWF (0.778). Root Mean Square Error (RMSE) for H_s SWAN is smaller than H_s ECMWF. This shows the SWAN modeling more closely to the measurement results, in other words, the SWAN model setting is good.

4.3 Monsoonal Significant Wave Characteristics

Examples of the significant wave (H_s) and wind pattern models in east monsoon and west monsoon are presented in Fig.3, both also show normal conditions and extreme wave (typhoon) condition.

Wind patterns during east and west monsoon are distinctly recognized based on its direction. The east monsoon winds travel from southeast to northwest, while the west monsoon winds are the opposites. The east monsoon wind or Australian monsoon wind blows from Australia to the equator and is known as the dry season that peaks in June-July-August. The west monsoon wind or Asian monsoon wind blows from the Asian continent with water vapors that cause rain, so it is called the rainy season and reaches its peak in December-January-February. Wind data treated in accordance with

both monsoon wind patterns and can be seen in Fig. 3a and 3b (right).

In normal condition as depicted in Fig. 3a and 3b, H_s is strongly associated with the wind pattern. Although, occasionally there are cyclones coming from Indian Ocean (south of Java) or typhoon in the South China Sea region and causing a disturbance within model domains for up to 15 days. One of the examples is the Typhoon Manny, which was originated in the Western Pacific. Fig. 3c shows the generation of typhoon within model domains and it has significantly amplified the wave height.

In normal conditions, the wind speed 5-7 m/s produces H_s 0.5-1.2 meter (Fig. 3a and 3b), while at maximum H_s condition between July-December 1993, wind speed 8-15 m/s yield H_s 1-3 meters (Fig.3d).The relative maximum H_s in the model domain reaches 3.16 m. It is located in the south of Kalimantan (see Fig. 3d). Meanwhile, in Jepara coastal waters, the increasing maximum H_s is up to 1.41 m.

The results of statistical calculations for the four areas in the study area obtained the H_s min-max and average H_s (meter) in the east monsoon conditions for the Java Sea 0.43-0.99 (average 0.64) Karimata Strait 0.18- 0.98 (0.51), Malacca Strait 0.02-0.58 (0.24), South China Sea 0.09-1.21 (0.47) and for the west monsoon; Java Sea 0.08-2.44 (average 0.57) Karimata Strait 0.09-2.09 (0.56), Malacca Strait 0.07-0.77 (0.28), South China Sea 0.21-2.93 (0.97).

This results are suitable when compared to H_s for 9 years forecasting by Wicaksana et.al (2015) [14] where at the west monsoon in Karimata Strait of H_s 1.5-3 m (H_s SWAN 2.09 m) and Java Sea 0.5-2.5 m (H_s SWAN 2.44 m), while at the east monsoon in Karimata Strait H_s 1.5-2.5 m (H_s SWAN 0.98 m) and Java Sea 1-2 m (H_s SWAN 0.99 m). Suitable in question is data analysis results for 6 months entered in the range of 9-year forecasting results.

4.4 Future Works Application

This study is expected to support wave characteristic research based on wave forecasting for 10 years in the waters between Java, Sumatera and Kalimantan. The wave forecasting research needed 10-year wind data (2007 - 2016) from

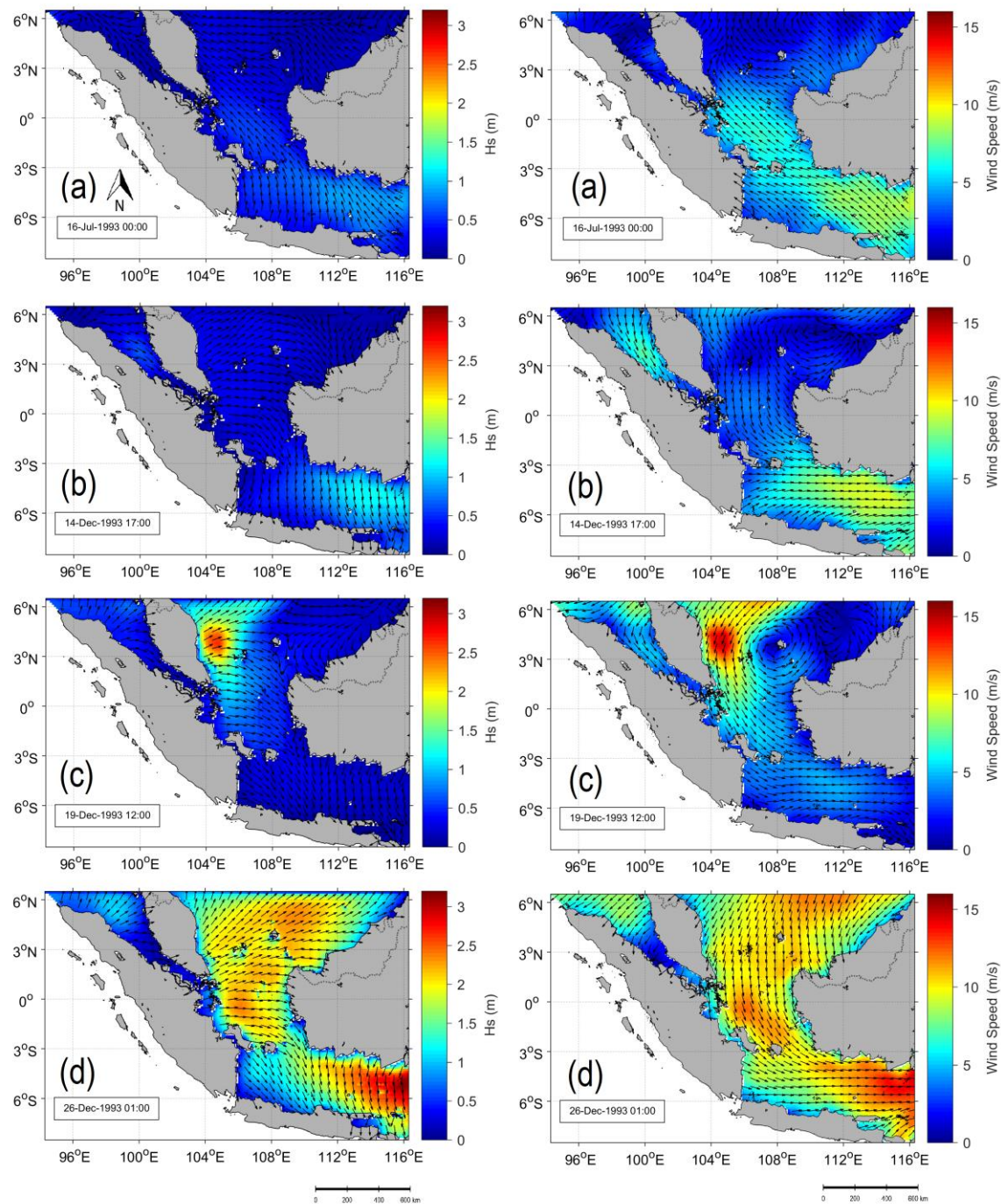


Fig. 3 Significant wave height with directional spreading (left) and wind speed (right) within the large model domain in different conditions: (a) east monsoon, (b) west monsoon, (c) typhoon Manny generation, and (d) relative maximum Hs for the period of July to December 1993.

ECMWF and bathymetry data from GEBCO where both data use the same resolution used in this study.

The results of the research are expected to help practitioners to plan the structure of the beach building, coastal protection, the structure of the building at sea, or marine structures. For example, as mentioned by Rathod et.al [15]; Piles used in marine structures are subjected to lateral loads from the impact of berthing ships and from waves. Piles used to support retaining walls, bridge piers and

abutments, and machinery foundations carry combinations of vertical and horizontal loads.

The 10-year wave data can be used as a basis to determine the probability of 25, 50, or even 100 years in the future. The use of significant wave heights with specific return periods is associated with the risk of planned building structures. The higher the risk value the longer return period is chosen.

Significant wave forecasting is also required for shipping safety. Until now the Karimata Strait (between south Sumatera and Kalimantan Island) is still a trading channel and the Java Sea becomes one of the important national service channels, especially in the present role in the Indonesian toll lane [14].

5. CONCLUSION

The result of forecasting with SWAN shows a wave distribution pattern corresponding to the buoy data, except for the duration of Oct-Nov 1993 for which the wave height of the measurement needs to be reconfirmed.

Refers to the Root Mean Square Error (RMSE) value (0,166) and correlation/ linear regression value (0,807), and the waveform pattern corresponding to the monsoon pattern, it can be stated that this SWAN model is valid.

The setting up of wave hindcast for Jepara waters will be helpful for improving the level of shallow sea wave hindcast in the waters between Java, Sumatera, and Kalimantan.

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