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Significant Wave Height Model Calibration in The Sea Around Banyuwangi and Bali

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Abstract

This paper describes significant wave height downscaling model in south sea around Banyuwangi and Bali. It utilizes 3rd Generation Simulating Wave Nearshore (SWAN) spectral model forced by ERA-5 Reanalysis data of wind and wave. The downscale is done using refined grid in Kuta Beach and Nusa Dua Beach. Model calibration conducted in the offshore and nearshore areas. The offshore wave results are validated using altimeter data, while the nearshore wave results are compared with site measurement in Kuta Beach and Nusa Dua Beach. A parametric study is performed to obtain model sensitivity and compared with observation, such as: wind multiplier factor, bottom friction coefficient, whitecapping, and wave breaking parameter. The model result gives good agreement with altimeter data. Indeed, the wind multiplier factor can be used as one calibration parameter in the wave model. The comparison with measured data shows good agreement in Kuta Beach, where the model can predict the nearshore wave transformation from offshore. Although, in Nusa Dua Beach the model nearshore wave transformation shows more dissipation if compared with wave measurement. Indeed, the downscaling process shows it can be used further in wave climate prediction after calibrated with measurement.

Keywords

Significant wave height, SWAN, model calibration, and sea around Banyuwangi and Bali

INTRODUCTION

Global warming caused by the greenhouse effect phenomenon is the cause of climate change in all parts of the world. Globally, the Earth's surface temperature has warmed by 1.1ºC in 2011-2020 when compared to the temperature in 1850-1900 and is predicted to increase up to 4ºC by 2100 [1]. The increasing trend of global warming has resulted in extreme climate phenomena such as heat waves, extreme rain, drought, tropical cyclones, and several other climate phenomena. These climate change phenomena have caused enormous damage and losses that are increasingly difficult to recover from, both on land, freshwater, and coastal areas and open oceans [1].

Climate change in the ocean both in coastal areas and in the open ocean results in changes in metocean characteristics including wind, waves, currents, sea surface temperature, and seawater salinity. Many previous studies have validated that climate change impacts wave characteristics such as significant wave height (Hs) and mean and peak wave periods. For example, there are changes in wave parameters in the form of Hs and certain return period Ts in the Mediterranean Sea [2][3]. Other research by conducting dynamic modelling of waves with several climate scenarios (RCP) also resulted in the same conclusion that the height and period of waves experiencing changes in the Atlantic Ocean [4] and globally around the world [5].

Changes in wave height due to climate change may affect the coastal and marine sectors in Banyuwangi and Bali. Tourism, fisheries, and transportation activities will be affected by extreme wave heights, as several extreme wave events have occurred. An extreme wave event resulted in fishermen at Muncar Fishing Port on July 2023 which reduced fish supply [6]. Approximately a year earlier, extreme waves also occurred where the wave height could reach 4 meters, which resulted in the operation of fishermen at the Muncar Fishing Port [7]. Many fishing boats that were docked sank due to the waves and strong winds. As a result of this incident, approximately 500 fishermen have stopped fishing from the previous few days. On July 2, 2023, there was also an extreme wave event at the Ketapang Port in Banyuwangi-Bali [8]. Waves at that time could reach a height of 4 meters, resulting in delays in ship departures. In Kuta Beach Bali, the same incident also occurred around May 2022 which resulted in severe abrasion conditions [9]. Wave heights at that time could reach 4 meters. More serious impacts such as damage to buildings are also felt due to extreme wave events. In April 2012, fishermen's houses on the coast of Muncar Fishing Port were damaged by extreme waves as high as 3 meters [10]. In another location, Pancer Harbor near to the Red Island Beach, the coastal building was damaged in March 2021 due to extreme waves in the last two years [11]. The buildings have suffered severe damage so that their utilities cannot be maximized.

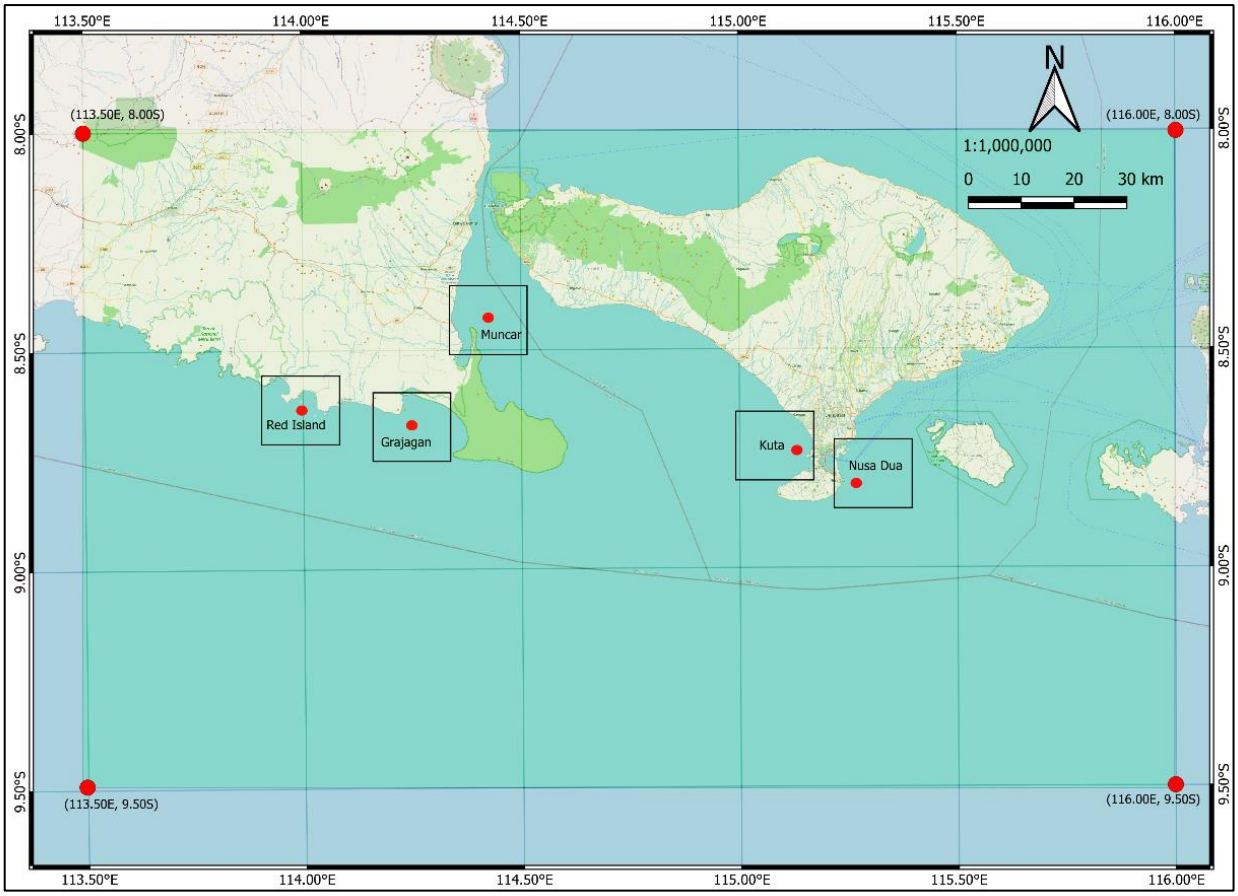


Figure 1 Research location

Based on the problem of changes in wave height characteristics that have the potential to affect various sectors in Banyuwangi and Bali, a study of the problem is needed. Wave modelling is one way that can be applied to determine the variability of waves that occur. Wave modeling covering the sea area around Banyuwangi and Bali has been carried out by previous researchers using a wave climate dynamic modeling approach with several climate scenarios (RCP) that produce wave height model outputs with low resolution. In addition, wave height can also be measured by satellites, but also still has a low resolution. Therefore, numerical model based on Simulating Wave Nearshore (SWAN) 3rd generation is performed with a sufficient scale. The model domain covers the entire coastline of Banyuwangi-Bali as seen in Figure 1. It uses several grid levels with graded sizes to produce model outputs with high resolution or have good wave height variability throughout the model domain. The wave model was also created specifically to model significant wave heights at several important objects located in the sea around Banyuwangi and Bali, such as Red Island Beach, Grajagan Fishing Port, Muncar Fishing Port, Kuta Beach, and Nusa Dua Beach. The simulation uses model scenarios with variation on several variables that make up the wave propagation, wave transformation, and wave dissipation. In addition, the modeled wave height will also be calibrated. Furthermore, this wave model can be a reference to be used in future studies on wave variability and extreme wave events specifically at several important objects such as Red Island Beach, Grajagan Fishing Port, Muncar Fishing Port, Kuta Beach, and Nusa Dua Beach.

RESEARCH SIGNIFICANCE

This research focuses on the downscaling of significant wave height from offshore waves to nearshore waves, which is expected to be able to represent extreme high wave events that have occurred. With the calibrated significant wave height time series and wave transformation data, the base of wave model can be used for further research such as extreme wave return periods. Therefore, it is very important to create a base of wave model that is representative of wave events in the field.

METHODOLOGY

A. DATA COLLECTION

The data used is secondary data, include maps of the sea area around Banyuwangi and Bali, historical data sourced from ERA5-Reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF) [REFX] with resolution of 0.5° x 0.5° consisting of hourly significant wave height (Hs), peak period, mean wave direction, wind speed, wind direction, and surface pressure, significant wave height (Hs) calibration data from JICA records in 1988 [12] and Hs data from satellite altimeter for period of January 2022 (https://las.aviso.altimetry.fr/) [13], BIG prediction tides data (https://srgi.big.go.id/map/pasut-prediction) [14], strategic object locations (test locations) in the sea around Banyuwangi and Bali, and the sea bathymetry data uses BATNAS, from Badan Informasi dan Geospasial (Indonesian Geospatial Agency, BIG) (https://tanahair.indonesia.go.id/demnas/#/batna) [15].

B. WAVE MODEL

The wave model was schematized as shown in Figure 2 with the descriptions shown in Table 1. The model was created with 3 grid levels in Kuta and Nusa Dua to perform smooth downscaling. Figure 3 shows an example of 3rd level grid with grid sizes that support the variability of modeled wave heights in Kuta and Nusa Dua. SWAN 3rd generation wave mode modeling is done with Delft3D-WAVE software. In SWAN, waves are expressed by a two-dimensional wave action density spectrum, including when non-linear phenomena dominate, for example, in the surf zone. Equation 1 shows the governing equation of SWAN using DELFT3D-WAVE.

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \quad (1)$$

The first term on the left side ($\frac{\partial}{\partial t}N$) of the above equation represents the local rate of change of the action density in time, the second ($\frac{\partial}{\partial x}c_x N$) and third ($\frac{\partial}{\partial y}c_y N$) terms represent the spreading of the action in spatial space (with spreading speeds c_x and c_y in x and y space). The fourth term ($\frac{\partial}{\partial \sigma}c_\sigma N$) represents the relative frequency shift due to variations in depth and current (with propagation speed c_σ in σ space). The fifth term ($\frac{\partial}{\partial \theta}c_\theta N$) represents the refraction induced by depth and current (with propagation speed c_θ in θ space). The propagation speed is taken from linear wave theory. The term $S(= S(\sigma,\theta))$ on the right-hand side of the action balance equation is the energy density source term representing the effects of generation, dissipation, and non-linear wave-wave interactions [16].

Waves propagating from offshore to nearshore have dissipation that is influenced by several parameters, such as bottom friction coefficient, whitecapping, alfawind, alpha and gamma depth-induced wave breaking. The bottom friction coefficient parameter of the SWAN model in the Delft3D-WAVE program can be selected from three formulations, Hasselmann et al. (1973) (JONSWAP), Collins (1972), and Madsen et al. (1988). In this study, the JONSWAP bottom friction coefficient formulation was chosen. Wave whitecapping in the program provides two formulation options that can be selected, Komen et al. and van der Westhuysen. The alfawind parameter as a representation of the multiplier value of wave generation by wind is important to be varied. The next parameters that affect the dissipation of significant wave height are alpha and gamma depth-induced wave breaking. The alpha parameter (α_{BJ}) is a coefficient that determines the magnitude of wave dissipation, while the gamma parameter (γ_{BJ}) is the wave breaking index or the ratio value between the maximum possible wave height and water depth. The definition of the two parameters is taken from the theory developed by Batthes and Janssen's (1978). The total dissipation due to depth-induced wave breaking is defined by the equation 2 [17].

$$D_{tot} = -\frac{1}{4}\alpha_{BJ} Q_b \bar{f} {H_m}^2 \quad (2)$$

α_{BJ} is a coefficient proportional to the magnitude of dissipation, Q_b is a representation of the breakers fraction, $\bar{f}$ is the mean frequency of the wave, and H_m is the maximum possible wave height. H_m is defined by equation 3. Equation 4 is a simplification of equation 3 for values of $k_p d \rightarrow 0$, resulting in $H_m = \gamma_{BJ} d$ which represents the depth-related wave height limit and is determined by the breaker index (γ_{BJ}) [17].

$$H_m = 0.88{k_p}^{-1}\tanh(\gamma_{BJ} k_p d/0.88) \quad (3)$$

$$H_m = \gamma_{BJ} d \quad (4)$$

The values of alpha (α_{BJ}) and gamma (γ_{BJ}) have been set in the Delft3D-WAVE program manual based on the 3rd mode wave generation. The alpha value (α_{BJ}) ranges from 0.1-10 with a default value of 1, while the gamma value (γ_{BJ}) ranges from 0.55-1.2 with a default value of 0.73 [16]. There is a study that explains the value of gamma (γ_{BJ}) based on depth-induced wave breaking modeling by processing several datasets from laboratory experimental data and field data (Amelander Zeegat, Lake Sloten, Lake Ijssel, Lake George, Boers (1996) and BJ78, and Duck). The study varied the value of gamma (γ_{BJ}) in the range 0.3-1.2. It was concluded that gamma (γ_{BJ}) has the smallest bias in the range of 0.73 and the largest bias in the range of 0.3 [17]. However, because the condition of each nearshore area has its own characteristics, it is necessary to vary the value of gamma (γ_{BJ}) and then conduct a sensitivity analysis.

C. MODEL SCENARIO

The model scenarios are created by varying several SWAN parameters including the bottom roughness coefficient, whitecapping, wave breaking parameters, and alfawind. The bottom roughness coefficient affects the dissipation of wave due to bed friction. Whitecapping is wave dissipation caused by steepness in deep water where some air enters the water near the surface, forming a white-looking emulsion of water and air bubble. Wave breaking parameters (α_{BJ} and γ_{BJ} depth induced breaking) is the driver parameter of wave breaking event which explained in chapter B. Alfawind is the multiplier value of wave generation by wind as explained in chapter B. All those parameters are important to affect the wave propagation phenomena.

In this study, the calibration was carried out in two stages, the first stage was a calibration of the offshore alfawind parameters by comparing the model results to the significant wave height data from the altimeter satellite in January 2021. The objective of the first stage is to obtain the value of the alfawind parameter that is representative of the conditions in the field and to determine the effect of the value of the bottom friction coefficient parameter and the whitecapping equation in the field. Six scenarios which include all the variation of alfawind, bottom friction coefficient, and whitecapping from this first stage of calibration can be seen in Table 2. The second stage of calibration is to analyze significant wave height in the offshore and nearshore area by varying the bottom friction coefficient, whitecapping, and depth-induced wave breaking (alpha (α_{BJ}) and gamma (γ_{BJ})) parameters with the objective to determine its effect on wave generation that occurs. This scenario can be seen in Table 3.

Table 2 Variation of SWAN parameters for calibration with satellite altimeter data

Scen.	Parameters		
	AlfaWind	Bottom Friction Coeff.	Whitecapping
1	1	JONSWAP (0.067 m^2/s^3)	Komen et al.
2	1	JONSWAP (0.067 m^2/s^3)	Westhuysen
3	2	JONSWAP (0.067 m^2/s^3)	Komen et al.
4	2	JONSWAP (0.067 m^2/s^3)	Westhuysen
5	1	JONSWAP (0.0335 m^2/s^3)	Westhuysen
6	1	JONSWAP (0.1005 m^2/s^3)	Westhuysen

Table 3 Variation of SWAN parameters for calibration with JICA (1988) recording data

Scen.	Parameters				
	Bottom Friction Coeff.	White-capping	Alfa-wind	α_{BJ}	γ_{BJ}
1	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	1	0.73
2	JONSWAP (0.0335 m^2/s^3)	Westhuysen	1	1	0.73
3	JONSWAP (0.067 m^2/s^3)	Komen et al.	1	1	0.73
4	JONSWAP (0.067 m^2/s^3)	Westhuysen	1	1	0.73
5	JONSWAP (0.1005 m^2/s^3)	Komen et al.	1	1	0.73
6	JONSWAP (0.1005 m^2/s^3)	Westhuysen	1	1	0.73
7	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	1.25	0.73
8	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	1.25	0.55
9	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	2	0.55
10	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	3	0.55
11	JONSWAP (0.0335 m^2/s^3)	Komen et al.	1	1	0.40

D. MODEL CALIBRATION

Model calibration was conducted by comparing the SWAN model output of significant wave height with the significant wave height from satellite altimeter on 1 to 31 January 2021, and JICA 1988 smoothed (6 hours) data records in Nusa Dua and Kuta Beach during March 21-26, 1988, May 11-16, 1988, and June 10-17, 1988. Calibration with satellite data was conducted to evaluate the model output significant wave height in the offshore area. The calibration location points can be seen in Table 4 or in Figure 3. Calibration with the record data of JICA 1988 was conducted to evaluate the model output significant wave height in the nearshore and offshore areas. The evaluation was conducted by calculating the Mean Absolute Percentage Error (MAPE) and considering the correlation coefficient (R) and Root Mean Square Error (RMSE) which can be calculated using equations 5, 6, and 7 with the criteria in Table 5 [18] and Table 6 [19].

Table 4 Calibration location of wave model

Gauge Point	Coordinate (UTM)	
	X	Y
Altimeter Point	280129.00	9004547.00
Nusa Dua Offshore	305916.63	9027957.37
Nusa Dua Nearshore	305664.08	9027752.84
Kuta Offshore	296241.52	9033399.13
Kuta Nearshore	297429.12	9033665.36

$$MAPE = \frac{1}{n}\sum\left(\frac{|y_i - x_i|}{y_i}\right) \times 100\% \tag{5}$$

where:

x_i = simulation result data
y_i = comparison data
n = number of data

$$R = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{7}$$

where:

x_i = simulation result data
y_i = comparison data
$\bar{x}$ = average value of simulated data
$\bar{y}$ = average value of comparison data
n = number of data

Table 5 MAPE value criteria

MAPE	Interpretation
<10%	Very good
10% - 20%	Good
20% - 50%	Enough
>50%	Bad

Table 6 R value criteria

R	Interpretation
0.800 – 1.000	Very strong
0.600 – 0.799	Strong
0.400 – 0.599	Medium
0.200 – 0.399	Low
0.000 – 0.199	Very low

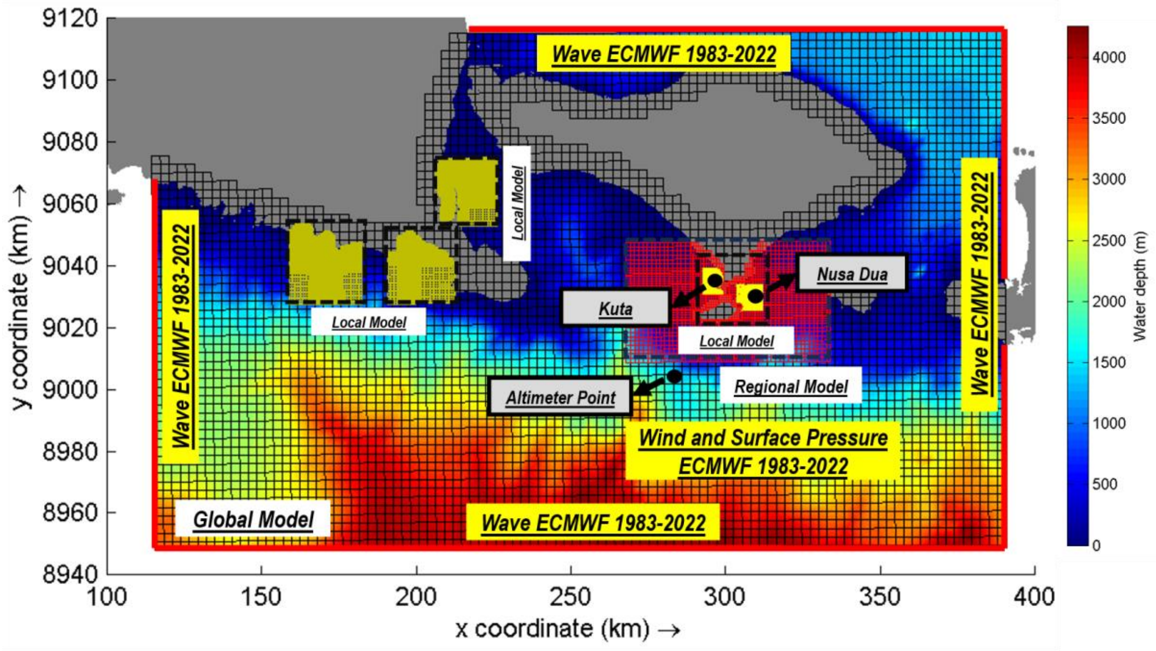
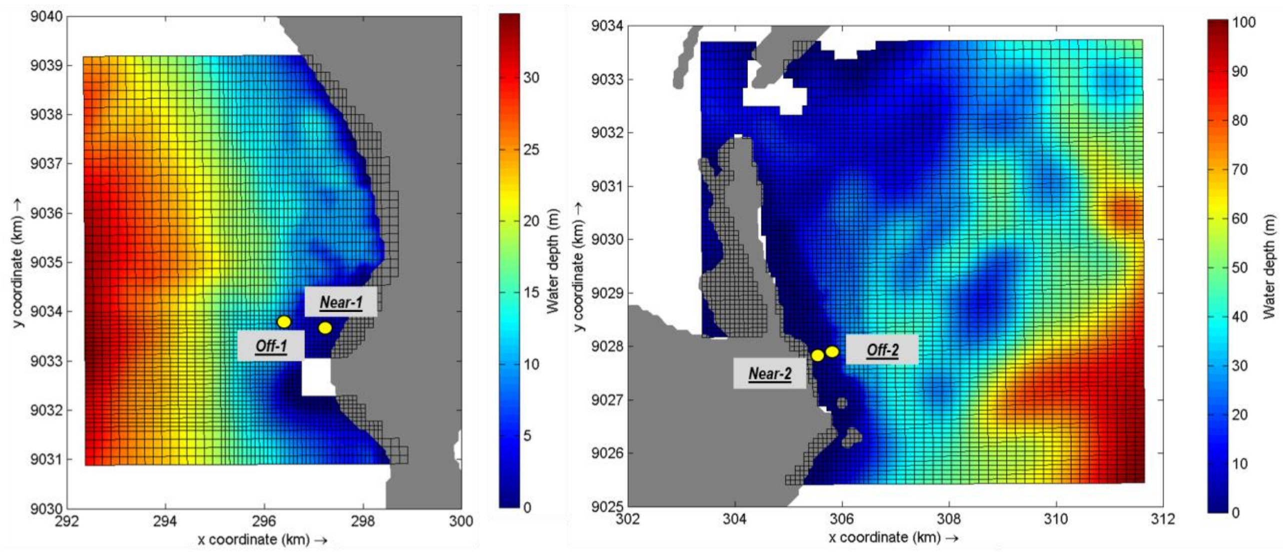


Figure 2 Schematization of wave model



(a). Kuta (b). Nusa Dua

Figure 3 Kuta and Nusa Dua model bathymetry

Table 1 Wave model description

No.	Nesting to Level	Grid Size	Boundary Conditions Type	Boundary Conditions Definition
Level 1 : Global Grid				
1	-	2738 m x 2738 m (0.025° x 0.025°)	Wave	Total wave from ECMWF 1983-2022
2	-		Wind	Wind from ECMWF 1983-2022
3	-		Surface Pressure	Surface pressure from ECMWF 1983-2022
Level 2: Regional Grid				
1	Level 1	676 m x 676 m (0.0061° x 0.0061°)	Wave	Level 1 simulation result
2	Level 1		Wind	Wind from ECMWF 1983-2022
3	Level 1		Surface Pressure	Surface pressure from ECMWF 1983-2022
Level 2: Local Grid (Red Island, Grajagan, and Muncar)				
1	Level 1	306 m x 306 m (0.00275° x 0.00275°)	Wave	Level 1 simulation result
2	Level 1		Wind	Wind from ECMWF 1983-2022
3	Level 1		Surface Pressure	Surface pressure from ECMWF 1983-2022
Level 3: Local Grid (Kuta and Nusa Dua)				
1	Level 2	86 m x 86 m (0.00077° x 0.00077°)	Wave	Level 2 simulation result
2	Level 2		Wind	Wind from ECMWF 1983-2022
3	Level 2		Surface Pressure	Surface pressure from ECMWF 1983-2022

RESULTS AND DISCUSSIONS

A. WAVE HEIGHT TIME SERIES CALIBRATION USING SATELLITE ALTIMETER DATA

Figure 4 shows that the significant wave height generated with an alfawind value of 1 has a better data distribution. The wave pattern (up and down as a function of time) and the significant wave height of the model output show less error when compared to the significant wave height generated with an alfawind value of 2. From these results, it can be concluded that the alfawind value that is representative of the conditions in the field and can be used as an input value in further modeling is 1.

From the scenarios in Table 2, it can be seen how the use of the whitecapping equation and the value of the bottom friction coefficient are affected. The results of scenario 1 and scenario 2 show that the wave whitecapping equation has insignificant influence on the significant wave height of the model output. In addition, the results of scenario 5 and scenario 6 show that the bottom friction coefficient has no effect on the modeled wave height. These results also validate that wave dissipation due to wave whitecapping and bottom friction and can be ignored due to its small effect on the generated offshore wave height.

Of the 6 scenarios, scenario 5 and scenario 6 have the smallest error with MAPE of 28.10% and RMSE of 0.46 m (Table 7). With these error values, the model output wave height can be categorized as sufficient to represent the calibration data [14]. In addition to using the MAPE and RMSE error value, calibration is also carried out by finding the correlation coefficient which aims to determine the level of correlation between the significant wave height of the model output and the wave height from the satellite altimeter. Figure 5 shows that the distribution of data with an alfawind value of 1 (scenarios 1, 2, 5, and 6) is better when compared to using an alfawind of 2. Scenarios 5 and 6 which show the best results have an R value of 0.745 which can be classified into the strongly correlated category [19].

B. WAVE HEIGHT TIME SERIES CALIBRATION USING JICA (1988) RECORDING DATA

Based on the overall results shown in Figure 6 and Figure 7, there is a relatively significant difference in significant wave height between the model output and JICA (1988) recording data at both offshore and nearshore measurement sites. The time series pattern of significant wave height (up and down of wave height as a function of time) is not well-modeled. For example, at Nusa Dua offshore, the model output on May 11-16, 1988 showed an under-prediction condition while that on June 10-17, 1988 showed an over-prediction condition and did not show the same up and down pattern in the two time spans. If we look back at the model output of the significant wave height at the offshore location compared to the satellite altimeter data (Figure 4) the results show that the wave height shows the same pattern with a relatively small error. This result shows that it is doubtful that the model is representative of the conditions in the field. Therefore, it is necessary to calibrate with other methods to be able to assess the validity of the model.

The significant wave height variation in the nearshore is related to the wave dissipation parameters (bottom frcition coefficient, whitecapping, and depth-induced wave breaking). The model outputs at the nearshore location from 11 scenarios are not good enough with varied and fluctuating conditions, and have different up and down patterns, indicating that wave dissipation needs to be optimized to obtain wave heights with smaller errors when compared to the recorded data. The overall significant wave height output at the nearshore location shows over-prediction results. The over-prediction condition means that the wave height dissipation that occurs is actually not large enough, so the wave height still tends to be higher when compared to the recorded data. Even though if the variation of wave height parameters with one of the scenarios set using the gamma parameter (depth-induced wave breaking) has been reduced to a value of 0.4 (scenario 11) which is smaller than the default gamma value of the Delft3D-WAVE program (0.55), the model output has not shown good results. Nevertheless, with reference to the MAPE and RMSE evaluation parameters, scenario 11 showed the best results with MAPE values reaching 29.80% (offshore) and 47.31% (nearshore), while RMSE values reaching 0.613 m (offshore) and 0.232 m (nearshore) in Kuta on June 10-17, 1988. The overall MAPE and RMSE evaluation results are shown in Table 8.

C. WAVE TRANSFORMATION CALIBRATION

To obtain a better justification of the model parameters, another calibration was conducted by analyzing the relationship between the ratio of wave height (H/H_0) and relative water depth (h/H_0). Figure 8 shows the graph of the relationship between wave height ratio and relative water depth recorded by JICA (1988), which is used as a reference to compare with the model output. This graph is a unitless graph that is representative of the wave height dissipation and wave transformation phenomenon due to refraction and shoaling effect ($H/H_0 = Ks \times Kr$) occurring in Nusa Dua and Kuta seas based on the data recorded at offshore and nearshore wave measurement points [20]. H is the wave height at the nearshore recording location, H_0 is the wave height at the offshore recording location, and *h* is the water depth at the nearshore measurement location. There is a trend line from the data distribution with a slope of 0.37 ($y = 0.37x - 0.08$). The slope of the graph also represents the breaking wave phenomenon. The ratio between the values of H/H_0 on the x-axis and h/H_0 on the y-axis is the value of H/h, in other words, the ratio between wave height and water depth at the nearshore measurement point (Kuta and Nusa Dua). According to Munk (1949) in CERC 1984, waves will break if the value of H/h = 0.78 [20]. However, in this modeling, the value of H/h is set to 0.4 (scenario 11) which is the gamma value of depth-induced wave breaking. The value of H/h = 0.37 ($0.37 < 0.4$) indicates that the waves have not broken at the nearshore measurement point at both location.

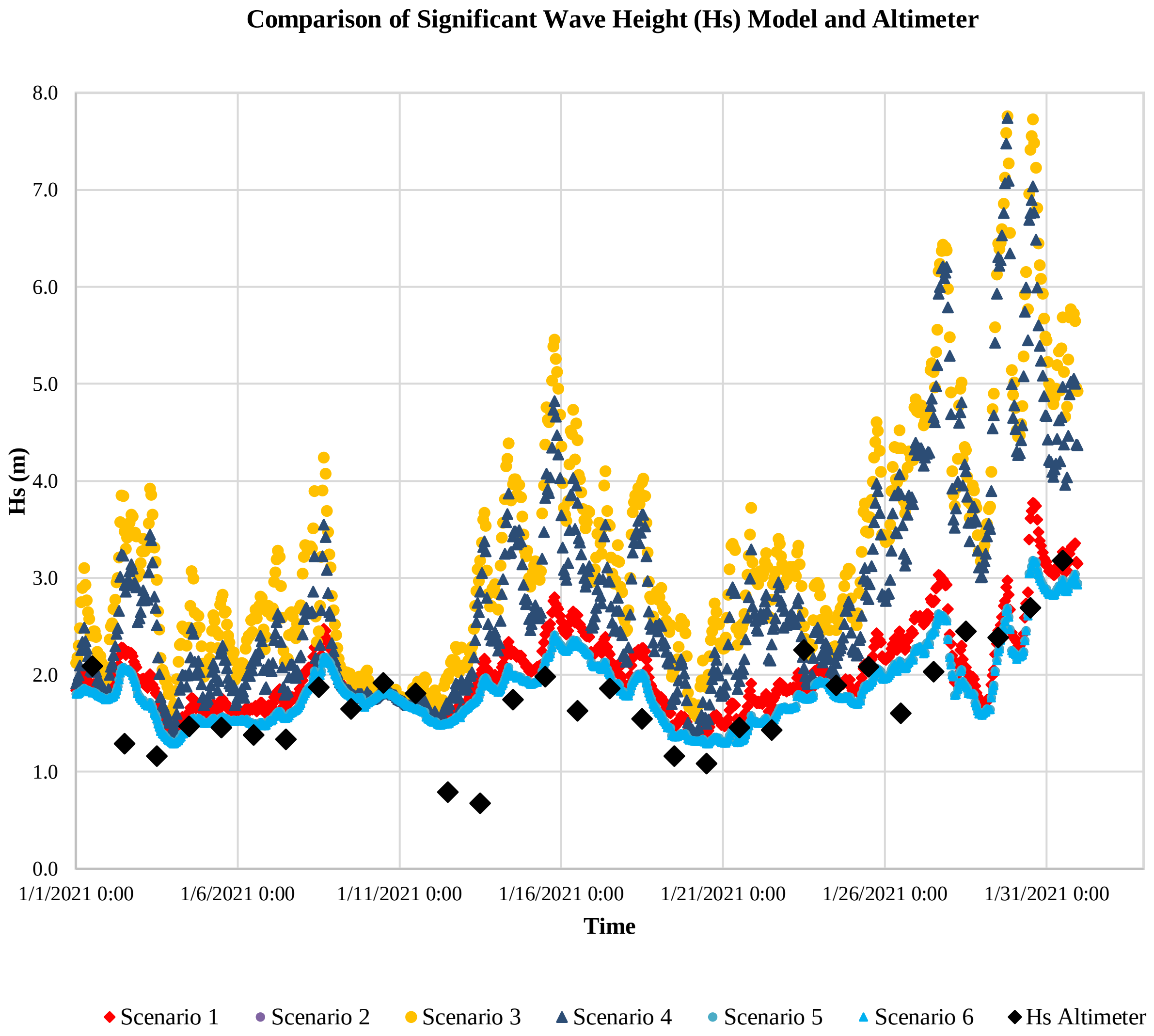


Figure 4 Comparison between Hs_{model} and $Hs_{altimeter}$ on January 1-31, 2022

The wave height model outputs at the offshore and nearshore measurement locations are plotted into graphs of the relationship between the ratio of wave height and relative water depth as shown in Figure 9 and Figure 10. The trend line which shows the slope of the data distribution on these graphs for each scenario can also be seen. In addition, the strength of the correlation between wave height ratio and relative water depth is also calculated using the R value criteria shown in Table 9. The model output of scenario 11 shows the best result with H/h = 0.21 in Kuta and H/h = 0.15 in Nusa Dua, and R value = 0.91, which means that the two variables have a very strong correlation.

When observed further, Figure 9 and Figure 10 show a flat distribution of H/H_0 value data at a certain value. This condition can be explained through the concept of the Ks (Coefficient of Shoaling) value which has a flat data distribution pattern at a certain value. Theoretically, H = Ks x Kr x H_0, if the refraction effect (Kr) is not taken into consideration, then the value of Ks = H/H_0. In addition, the Ks value is only affected by the water depth (h) and wave period (T). Therefore, the value of H/H_0 or Ks will always be flat at a certain value.

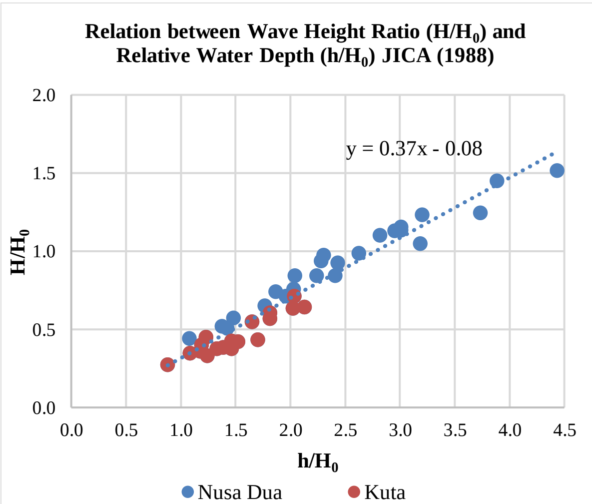


Figure 8 Relation between wave height ratio and relative water depth recorded by JICA (1988)

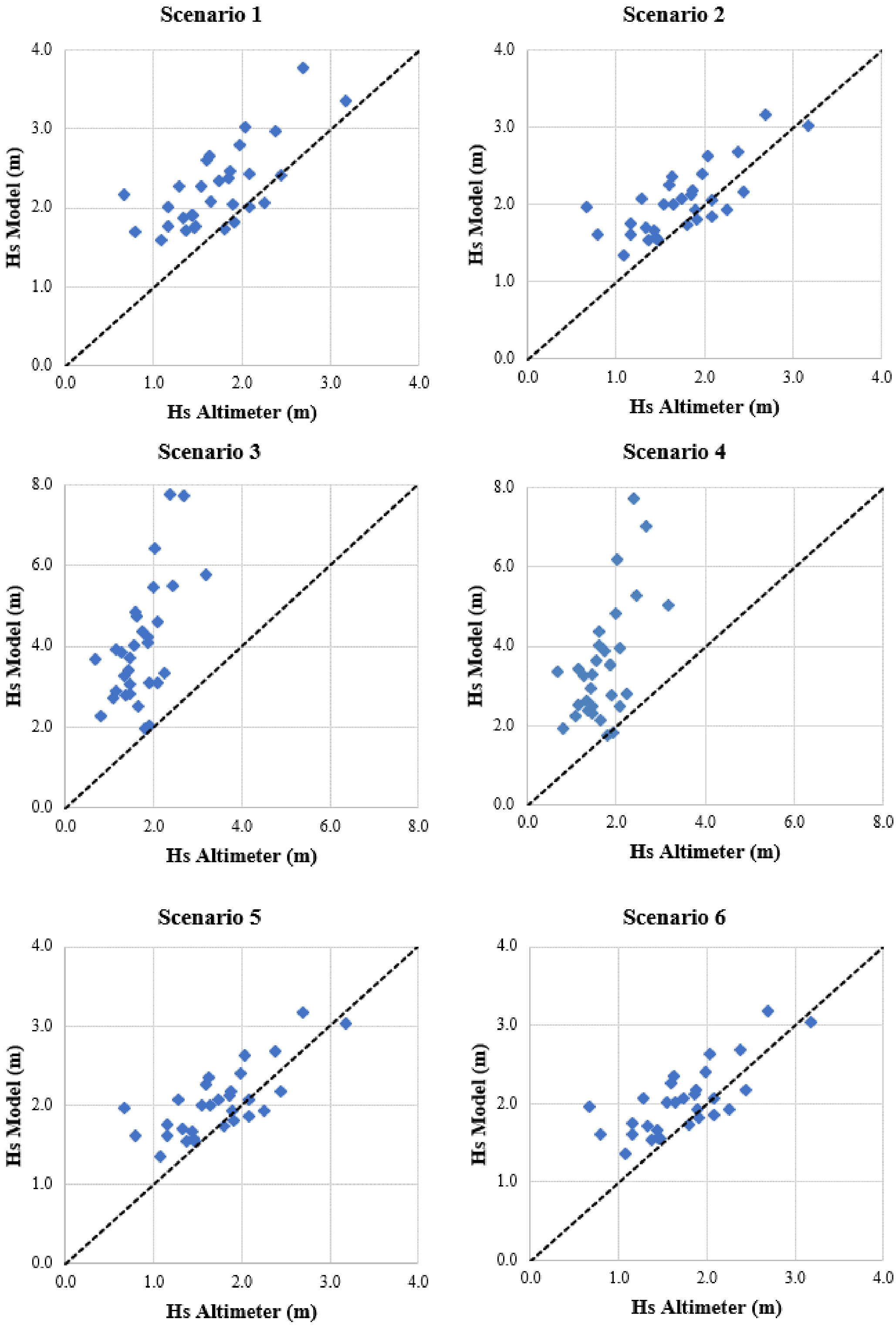


Figure 5 Correlation diagram between Hs_{model} and $Hs_{altimeter}$

Table 7 Recapitulation of R, MAPE, and RMSE values (altimeter data calibration)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
R Value	0.707	0.744	0.614	0.598	0.745	0.745
MAPE Value	40.57%	28.13%	142.90%	114.13%	28.10%	28.10%
RMSE Value	0.662	0.460	2.581	2.190	0.460	0.460

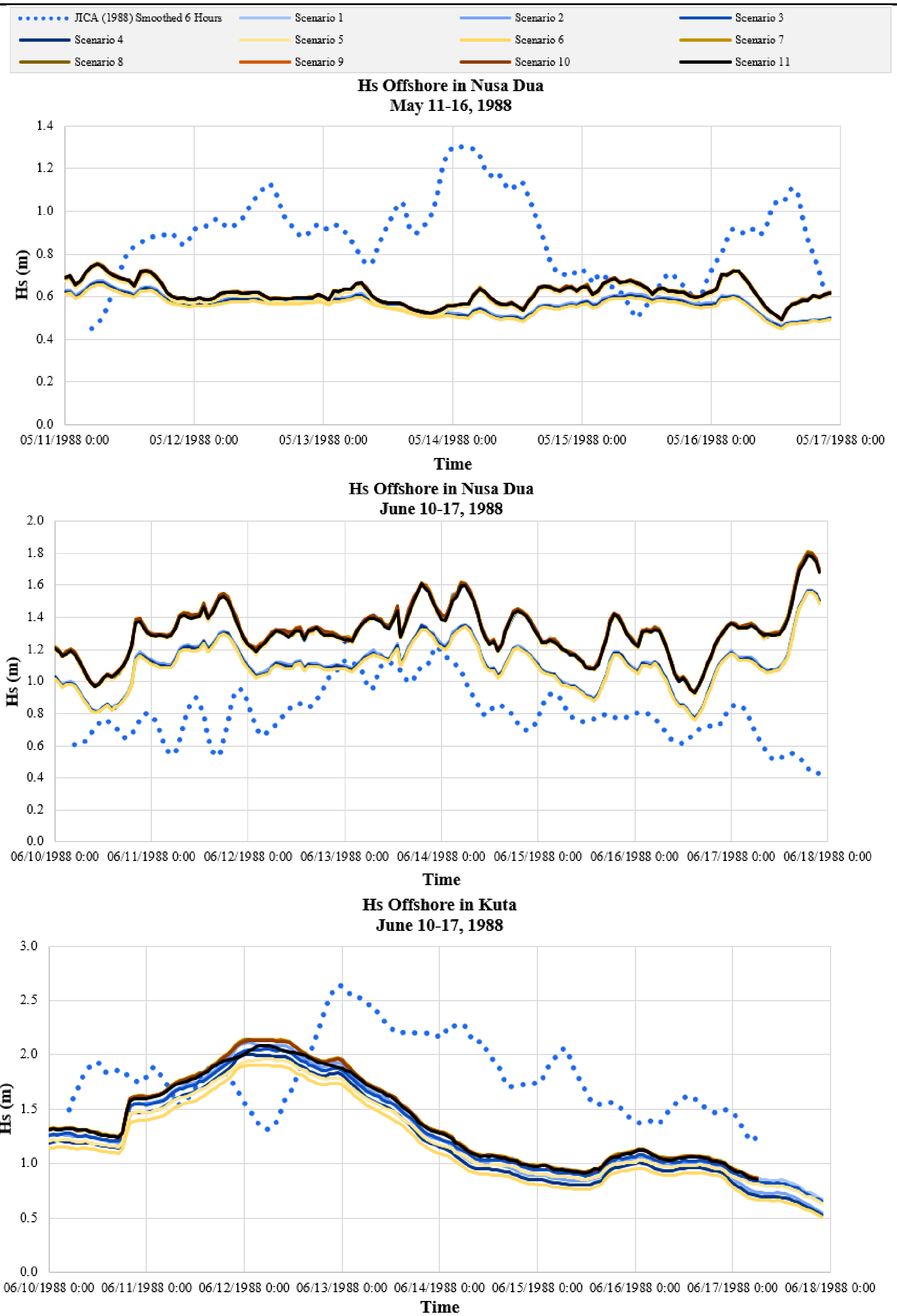


Figure 6 Comparison between Hs (model) and Hs (model) in Nusa Dua and Kuta at Offshore Point Measurement

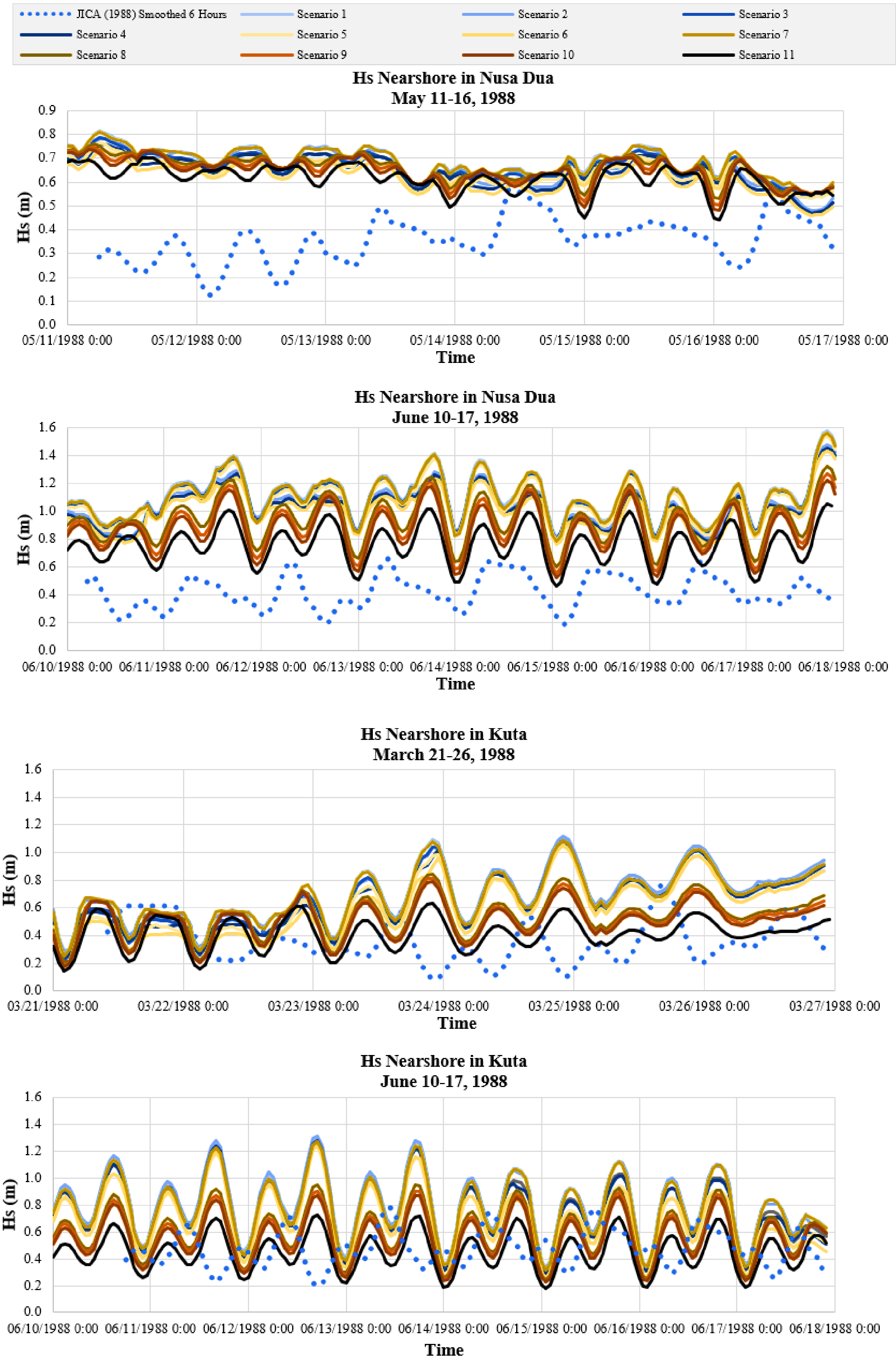


Figure 7 Comparison between Hs (model) and Hs (JICA) in Nusa Dua and Kuta at Nearshore Point Measurement

Table 8 Recapitulation of MAPE and RMSE values (JICA (1988) recording data calibration)

Nusa Dua

Location	Scen.	May 11-16, 1988		June 10-17, 1988	
		MAPE	RMSE	MAPE	RMSE
Offshore	1	30.33%	0.347	73.17%	0.562
	2	34.08%	0.380	46.97%	0.381
	3	30.86%	0.353	72.17%	0.555
	4	34.83%	0.387	45.86%	0.374
	5	31.45%	0.358	71.26%	0.548
	6	35.59%	0.393	44.76%	0.367
Nearshore	1	124.06%	0.372	197.65%	0.732
	2	117.63%	0.354	178.96%	0.660
	3	110.35%	0.350	192.73%	0.713
	4	110.11%	0.332	173.20%	0.639
	5	109.68%	0.329	187.82%	0.695
	6	102.90%	0.310	187.82%	0.618
Offshore	7	30.31%	0.347	73.37%	0.563
	8	30.33%	0.347	73.00%	0.560
	9	30.36%	0.347	73.21%	0.562
	10	30.34%	0.347	73.36%	0.563
	11	30.40%	0.348	71.92%	0.552
Nearshore	7	123.44%	0.370	193.67%	0.718
	8	115.22%	0.345	151.45%	0.567
	9	112.49%	0.337	140.42%	0.529
	10	110.10%	0.330	131.50%	0.499
	11	100.91%	0.303	103.72%	0.395

Kuta

Location	Scen.	March 21-26, 1988		June 10-17, 1988	
		MAPE	RMSE	MAPE	RMSE
Offshore	1	-	-	29.88%	0.610
	2	-	-	32.69%	0.663
	3	-	-	31.25%	0.640
	4	-	-	34.39%	0.700
	5	-	-	32.76%	0.673
	6	-	-	32.76%	0.738
Nearshore	1	184.53%	0.477	93.58%	0.431
	2	182.07%	0.471	93.89%	0.434
	3	172.24%	0.447	85.59%	0.397
	4	168.73%	0.439	85.48%	0.399
	5	160.33%	0.417	78.62%	0.365
	6	156.21%	0.409	77.80%	0.365
Offshore	7	-	-	29.88%	0.610
	8	-	-	30.06%	0.613
	9	-	-	30.10%	0.614
	10	-	-	30.10%	0.614
	11	-	-	29.80%	0.613
Nearshore	7	179.23%	0.463	90.07%	0.415
	8	120.94%	0.313	61.90%	0.282
	9	113.62%	0.295	58.72%	0.267
	10	108.17%	0.282	56.36%	0.257
	11	80.69%	0.221	47.31%	0.232

The verification of the distribution pattern of Ks values that will be flat at a certain value and only influenced by depth (h) and wave period (T) is shown in Figure 11 and Figure 12. Figure 11 shows the plot of Ks values resulting from scenario 11, while Figure 12 shows the example plot of Ks values in general for several different wave periods with the depth of 2 m and H_0 in the range of 0.1 – 2.0 m. The limit value of H/h (the ratio between H/H_0 and h/H_0 or the slope of the data) indicates the limit of the wave breaking phenomenon, where the wave will break when $H/h > 0.78$ (CERC, 1984) or $H/h > 0.4$ (gamma value of depth-induced wave breaking). From this boundary, the area above the boundary line indicates that the wave has broken and below the line indicates that the wave has not broken.

There are interesting things that can be seen from the visualization of data distribution. Although the distribution of H/H_0 and/or Ks data from the model output shows a flat condition, the flat condition is still relatively fluctuating due to the time series of H_0 data which is influenced by wind and h which is influenced by tides. In other hand, the measurement data of JICA (1988) shows a linear H/H_0 trend. Theoretically, the plot of H/H_0 values should be flat at a certain H/H_0 value. It can also be seen that there are outlier data (marked with circles) in the JICA recording. The data may be recorded by JICA due to the local wind that generates waves around the nearshore measurement location. The local wind adds significant wave height around the location. Another possibility is that the model is not fully representative of the field conditions.

D. CALIBRATED PARAMETERS

Based on the calibration with wave height time series data (satellite altimeter and JICA (1988) records) and the relationship graph between wave height ratio (H/H_0) and relative water depth (h/H_0), scenario 11 proved to show the best results among other scenarios. The parameters varied in scenario 11 consisted of alfawind = 1, bottom friction coefficient = JONSWAP (0.0335 m^2/s^3), whitecapping using Komen et al.'s formulation, and depth-induced wave breaking alpha and gamma values of 1 (α_{BJ}) and 0.4 (γ_{BJ}).

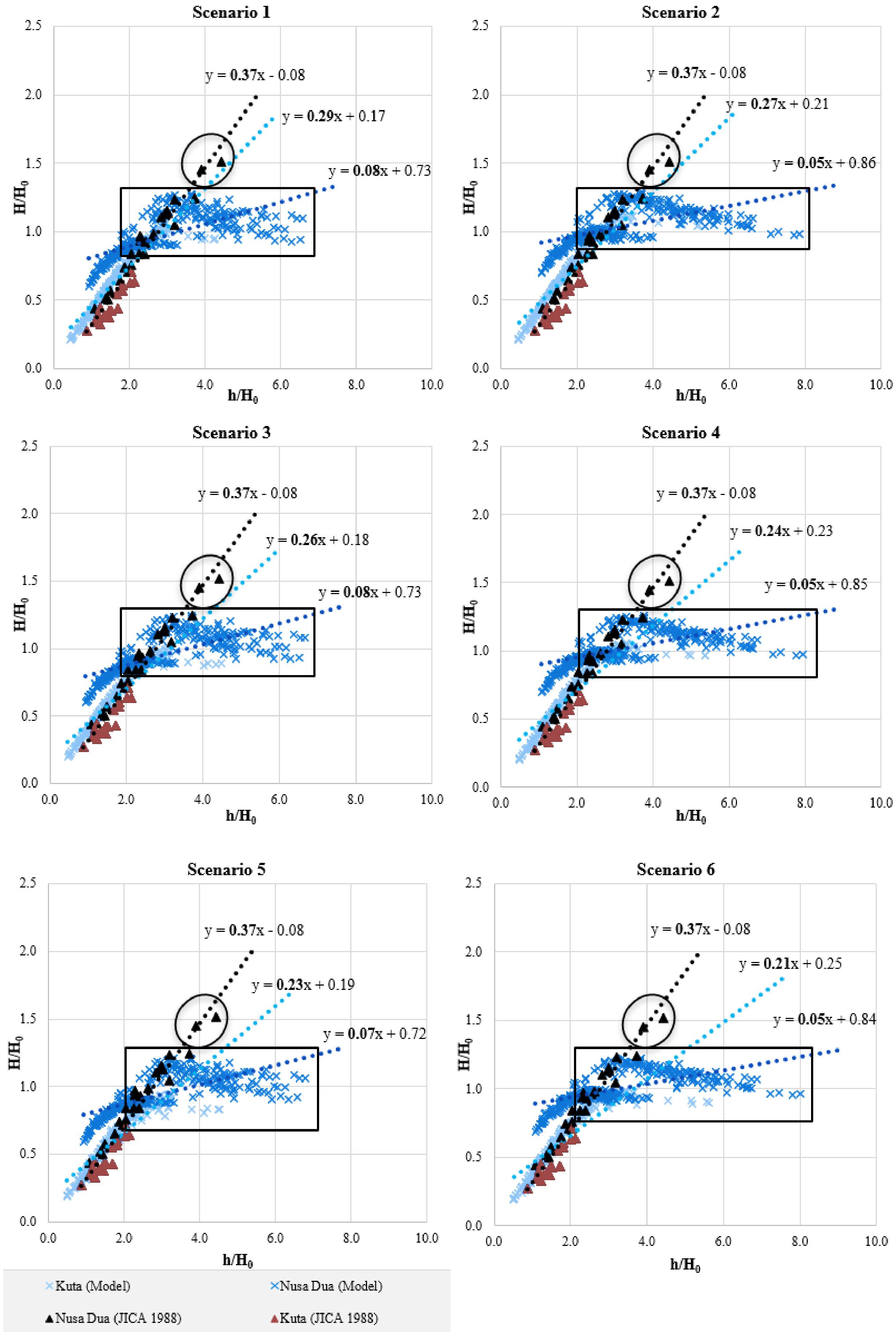
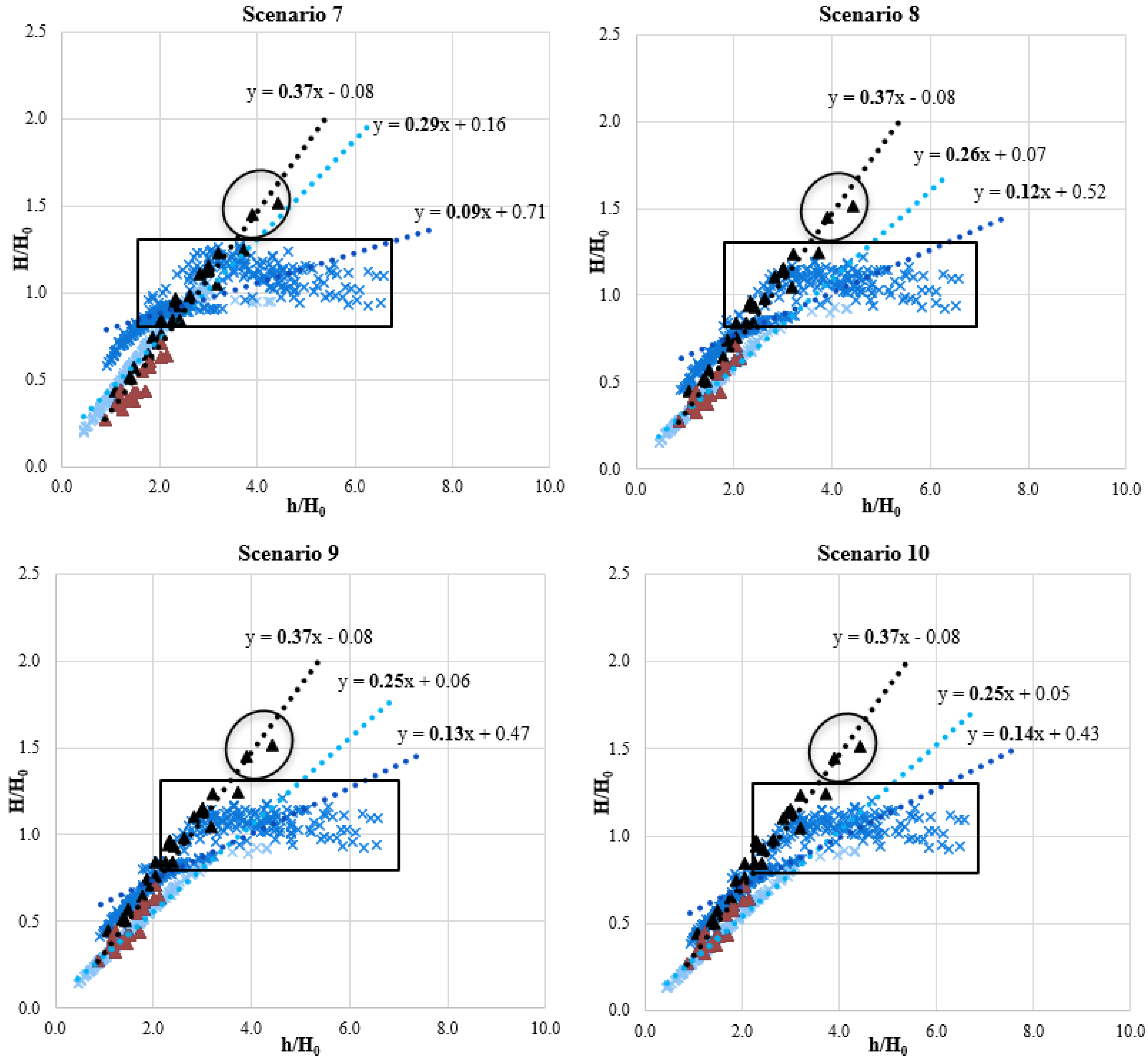


Figure 9 Relation between wave eight ratio and relative water depth (model output for scenario 1-6)



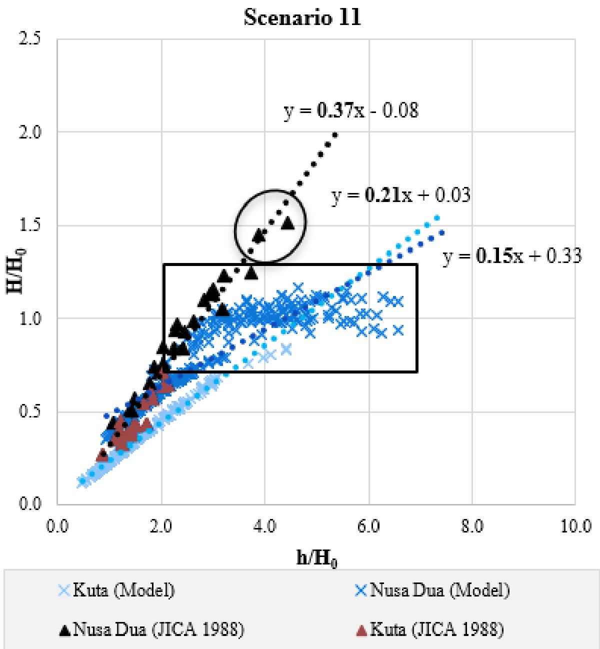


Table 9 Recapitulation of R value

Scenario	R Value
1	0.773
2	0.729
3	0.765
4	0.721
5	0.754
6	0.711
7	0.782
8	0.854
9	0.871
10	0.883
11	0.901

Figure 10 Relation between wave height ratio and relative water depth (model output for scenario 7-11) and recapitulation of R value

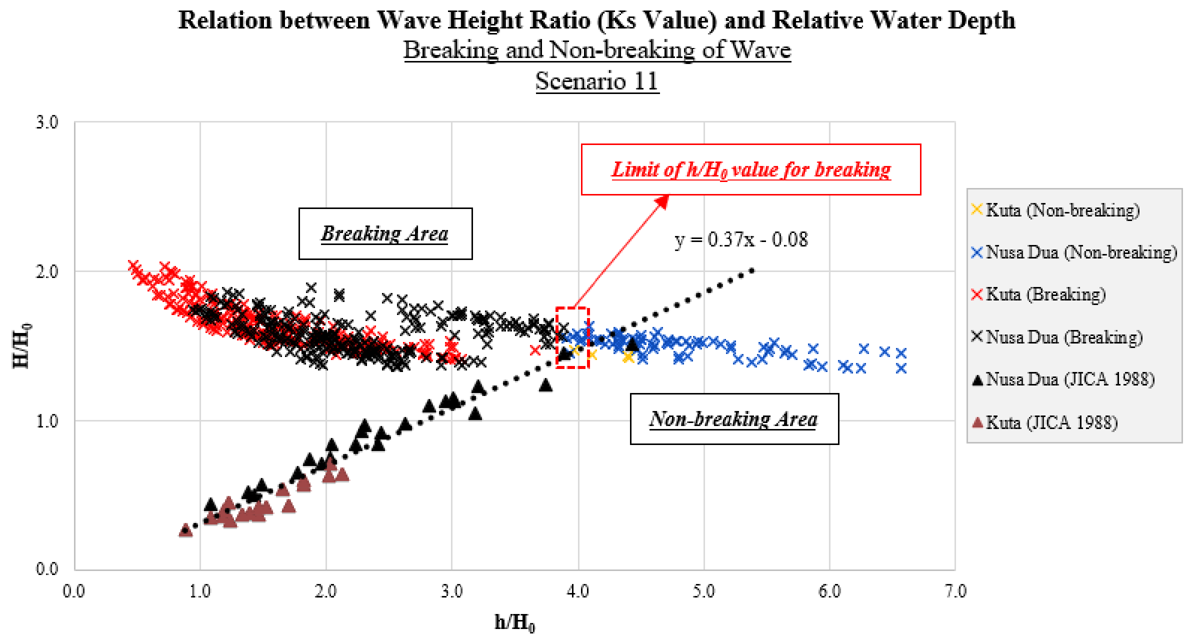


Figure 11 Relation between wave height ratio and relative water depth (model output of scenario 11)

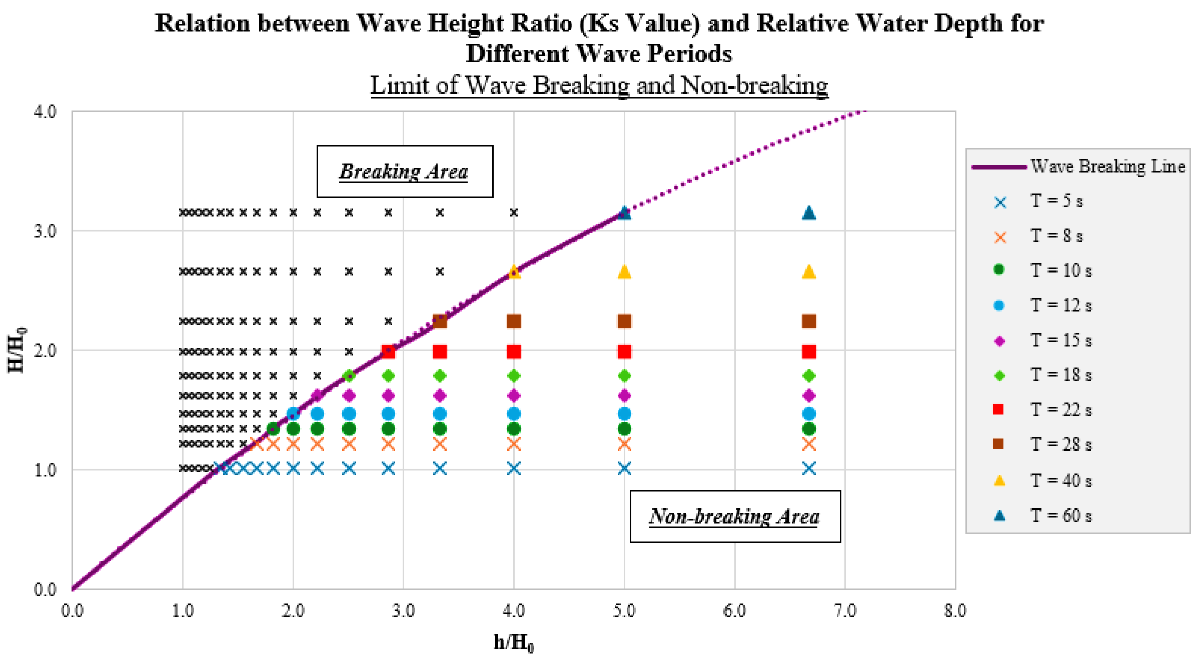


Figure 12 Relation between wave height ratio and relative water depth for different wave periods

With MAPE values that can reach 29.80% (offshore) and 47.31% (nearshore), while RMSE values that reach 0.613 m (offshore) and 0.232 m (nearshore) in Kuta on June 10-17, 1988, the scenario 11 model output still shows a relatively high error. Considering all the wave dissipation and transformation, it can be justified that the model can be used to replicate the conditions on the ground with a slope (H/h) of 0.21 in Kuta and 0.15 in Nusa Dua based on the output of scenario 11. The different variability of wave transformation between the model results and JICA (1988) recording data may be caused by other factors such as the accuracy of measurement data, the accuracy of the bathymetry model, and the model input wave data sourced from ECMWF (ERA5-Reanalysis data).

CONCLUSIONS

The significant wave height model in the sea around Banyuwangi and Bali has been created by applying the 3rd generation wave of SWAN. The model was created with the aim to be used as a base model that can be modified for other research purposes, such as the variability of extreme wave heights around the sea, especially in several important locations that have been detailed in the model, such as Red Island Beach, Grajagan Fishing Port, Muncar Fishing Port, Kuta Beach, and Nusa Dua Beach. ERA5-reanalysis data of total wave and wind used for model and wave height data from JICA (1988) and satellite altimeter data used for calibration process in offshore and nearshore. Calibration of the model is done by comparing wave height time series data and analyzing the wave transformation that occurs in the nearshore. The model calibration shows that all of parameters such as alfawind, bottom friction coefficient, whitecapping, and alpha & gamma (depth-induced wave breaking) were shown to affect the wave propagation in offshore and nearshore area. Scenario 11 with MAPE values that can reach 29.80% (offshore) and 47.31% (nearshore), while RMSE values that reach 0.613 m (offshore) and 0.232 m (nearshore) in Kuta on June 10-17, 1988, and with H/h = 0.21 (Kuta) and H/h = 0.15 (Nusa Dua), and R value = 0.91, proved to show the best results among other scenarios. The parameters varied in scenario 11 consisted of alfawind = 1, bottom friction coefficient = JONSWAP (0.0335 m^2/s^3), whitecapping using Komen et al.'s formulation, and depth-induced wave breaking alpha and gamma values of 1 (α_{BJ}) and 0.4 (γ_{BJ}).

For further research, it is important to consider the accuracy of bathymetry data, especially in small domain modeling. This is important because it is closely related to the propagation of waves that occur on the beach, thus affecting the transformation and dissipation of waves. In modeling to obtain wave height output in time series, the model output will produce a more valid model in accordance with field conditions that have complex variability over time. In addition, it is also important to pay attention to wave recording data in the field both in accuracy and in time that can represent the purpose of wave modeling.

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