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Impact Analysis of Tropical Cyclone Cempaka-Dahlia on Wave Heights in Indonesian Waters from Numerical Model and Altimetry Satellite

Wiwin Windupranata[1], Candida A.D.S. Nusantara[1], Dudy D. Wijaya[2], and Kosasih Prijatna[2]

[1]Research Group of Coastal, Marine and Maritime Engineering, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung
[2]Research Group of Geodesy, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung

Corresponding Author:
Wiwin Windupranata
w.windupranata@itb.ac.id

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Abstract

Indonesia is located side by side with the Pacific Ocean and the Indian Ocean where there are often tropical cyclones in these two oceans. As was the case some time ago in the Indian Ocean a tropical cyclone of Cempaka and Dahlia occurred which had a significant impact on Indonesian areas. Another impact felt is the disruption of economic activity in the area of tourism, ports, and power plants. Numerical modeling is carried out to simulate the phenomena of Cempaka and Dahlia tropical cyclones to determine the impacts caused especially in Lampung to Lombok areas. Numerical modeling is done using SWAN version 41.20. SWAN was chosen because it has good modeling calculations in coastal areas and is very suitable for wave analysis in coastal areas. The results of the modeling are verified by the significant wave height correlation coefficient from altimetry satellites that cross the tropical cyclones of Cempaka and Dahlia. The results showed a significant increase in wave height in the study area with an increase of up to 1028.31% at the observation point in Pelabuhan Ratu, West Java Province.

Keywords: waves, waves modeling, SWAN, tropical cyclone, Cempaka Dahlia

1. Introduction

Tropical cyclones are large-powered storms and have a low-pressure system that grows over warm waters and high wind speeds in more than half of the area surrounding its center. Sometimes at the center of tropical cyclones, a cyclone eye is formed which is a region with relatively low wind speeds and no clouds. The cyclone's eyes are surrounded by cyclone eyewall, which are ring-shaped areas that can reach 16 km in thickness, which are regions where there are the highest wind speed and large rainfall. The life span of a tropical cyclone ranges from 3 to 18 days on average. Because tropical cyclone energy is obtained from warm oceans, tropical cyclones will weaken or disappear when moving and entering cold waters or entering the land.

Tropical Cyclone Cempaka is a tropical depression that occurs in the southern part of Java. The cyclone is shown by the presence of ash from Mount Agung, Bali which leads to the west. Cempaka cyclone weakens when heading southwest. Tropical Cyclone Dahlia was first observed on November 24, 2017, when a tropical depression occurred about 1,500 km west of Jakarta. On December 1, Dahlia was intensified into a Category 2 tropical cyclone and reached its peak intensity six hours later with a minimum barometric pressure of 985 hPa [1]. In general, Tropical Cyclone Cempaka and Dahlia affect waters from Lampung Province to Lombok Island which are characterized by rising sea waves, strong winds, high-intensity of rain, floods, and landslides in the area [2]. Numerical modeling needs to be done to determine the impact of Tropical Cyclones Cempaka and Dahlia.

Numerical modeling is done using Simulated Wave Nearshore (SWAN) which is used to obtain a significant wave height (SWH) value. The value of the significant wave height (SWH) will then be used to determine the wave characteristics when the tropical cyclone cempaka and dahlia phenomena occur in ports, tourism places, and power plants site in the Lampung region to Lombok Island. Wave modeling during Cempaka and Dahlia Tropical Cyclones is expected to be able to determine the impact of these tropical cyclones. Wave modeling verification was carried out by comparing the significant wave height of the modeling results with significant wave height from the results of altimetry satellite observations that passed during the Cempaka and Dahlia Tropical Cyclones. The verification model results are presented in the form of a graph of the significant wave height between the significant wave height of the modeling results on the altimetry satellite and statistically seen from the correlation coefficient values of the significant wave height of the altimetry observation and modeling results.

2. Data and Methods

This research was conducted at the study area of Lampung Province to Lombok Island. This area was chosen because of its close to the Cempaka and Dahlia Tropical Cyclones so that the impact of the increase in wave height caused by the two cyclones can be identified. Observation of wave height increases is carried out by placing observation points in wave modeling in important areas such as tourism sites, ports, and power plants.

In wave modeling, bathymetry data and wind data are used as input data. The bathymetric data used comes from General Bathymetric Chart of the Oceans (GEBCO) with a resolution of 30"x30" and from BIG BATNAS with a resolution of 6"x6". The wind data used comes from the European Center for Medium-Range Weather Forecast (ECMWF) on 10 November 2017 - 5 December 2017 with a resolution of 0.125°x0.125° at 1-hour intervals. The results of wave modeling compared to the altimetry satellite wave height taken from the Radar Altimeter Database System (RADS) that passed in the study area during the Cempaka and Dahlia tropical cyclones. The data used in modeling can be seen in detail in Table 1.

Table 1: Data types and sources.

No.	Data Types	Source	Note
1	Bathymetry Data	General Bathymetric Chart of the Oceans (GEBCO)	Resolution: 30''x30'' Wilayah: South East Asia
		BATNAS BIG	Resolution: 6''x6'' Area: Lampung Province -- Lombok Island
2	Wind Data	European Centre for Medium-Range Weather Forecast (ECMWF)	Resolution: 0.125° x 0.125° Interval: 1 Hour Time: 10 Nov 2017 -- 5 Dec 2017
3	Altimetry Satellite	Radar Altimeter Database System (RADS)	Time: 26 Nov 2017 - 4 Dec 2017Area: 100.5° E -- 114° E; -14° S -- 0.5° S

2.1. SWAN Numerical Model

In the SWAN model, wave modeling changes the time series domain into a frequency domain using Fourier transforms. Existing sea level information is used in the calculation of the wave spectrum of variance or energy density E ("σ","θ"), which distributes wave energy (radians) to the frequency σ (observed in a reference frame moving with current velocity) and direction of propagation "θ" (normal direction to the wave peak of each spectral component. The spectral energy density function E ("σ","θ") becomes a function of space and time on a larger scale so that wave dynamics are considered in determining changes in the spectrum of space and time [3].

In coastal waters or shallow waters, several elements contribute to forming the Stot as stated in the following equation:

$$S_{tot} = S_{in} + S_{n13} + S_{n14} + S_{ds,w} + S_{ds,b} + S_{ds,br} \tag{1}$$

Where "S" _"in" is input from the wind, "S" _"n13 " is a triads wave interaction, "S" _"n14" is a quadruplets wave interaction, "S" _"ds,w" is a dissipation due to whitecapping, "S" _"ds,b" is a dissipation due to friction of the seabed, and "S" _"ds,br" is a dissipation due to breaking waves [3].

In this study, a spherical coordinate system was used. This is because the large observation area and batimetric input data also use a spherical coordinate system. In general, the spectral action equation used in the spherical coordinate system is:

$$\frac{\partial}{\partial t} + \frac{\partial c_{\lambda}}{\partial \lambda} + \frac{\partial c_{\varphi}}{\partial \varphi} + \frac{\partial c_{\sigma}}{\partial \sigma} + \frac{\partial c_{\theta}}{\partial \theta} = \frac{S_{tot}}{\sigma} \tag{2}$$

Where ("∂" "c" _"λ" "Ñ")/"∂λ" is the propagation of the wave action density in longitude, ("∂" "c" _"φ" "Ñ")/"∂φ" is propagation wave action density at latitude. Because "Ñ" is the action density in latitude and longitude, then "Ñ" = N.R2 cos θ where R is the radius of the earth and θ is the direction of the wave measured from the geographical east counterclockwise [3]. The equation above is reduced to get the energy equilibrium equation using the following equation:

$$\frac{\partial E}{\partial t} + \frac{\partial c_{\lambda} E}{\partial \lambda} + \frac{\partial c_{\varphi} E}{\partial \varphi} + \frac{\partial c_{\sigma} E}{\partial \sigma} + \frac{\partial c_{\theta} E}{\partial \theta} = S_{tot} \tag{3}$$

Where E is the energy density. Given that the SWAN wave interaction is based on action density it is necessary to reduce it to obtain energy density to calculate wave characteristics [4]. SWAN modeling produces significant wave height (Hs) through the following equation [4].

$$H_s = 4\sqrt{\iint E\,(\omega, \theta) d\omega d\theta} = 4\sqrt{\iint E\,(\sigma, \theta) d\sigma d\theta} \tag{4}$$

2.2. Altimetry Satellite

Altimetry satellites send microwave signals that will be reflected back by sea level. The time of reflecting microwaves is calculated to get the distance of the satellite to the surface of the sea, whereas for the height of the ocean wave obtained from the slope of the leading edge of the received altimetry signal. Dynamic sea level conditions make reflecting signals from altimetry satellites diverse (Figure 1). The wave height is proportional to the reflected wave time, based on the slope assumption of the waveform shape which is proportional to the wave amplitude [5].

2.3. Modeling Scenarios

The modeling in this study was carried out with the following scenario:

The land modeling domain is given a value of -999 so it does not enter into computational modeling. The nesting method is used to make models in smaller areas with boundary conditions from larger domains. In this study, there are 5 domains of modeling including:

(a) altimetry waveform at calm sea surface (b) altimetry waveform at rough sea surface

Figure 1: Wave height from altimetry satellite [**6**].

1. Southeast Asia domain which is located at 85 ° - 155 ° E and 19 °S - 19 °N with a spatial resolution of 12 'x 12'.
2. Lampung -- Lombok domain which is located at 99 ° - 118 ° E and 14 °S - 1 ° N with spatial resolutions of 2'30 "x 2'30".
3. Lampung - Banten domain which is located at 101 ° - 108 ° E and 8 ° S - 2 ° S with a spatial resolution of 1 'x 1'.
4. West Java - Central Java domain which is located at 106 ° - 112 ° E and 10 ° S - 5 ° S with a spatial resolution of 1 'x 1'.
5. East Java - Lombok which is located at 111 ° - 116 ° E and 11 ° S - 6 ° S with a spatial resolution of 1 'x 1'.

The Southeast Asian domain uses bathymetry data from GEBCO while the other domains use bathymetry data from BATNAS BIG.

The initial conditions at all points have zero wind speed values. This is due to the absence of prior modeling as input in modeling so that it begins with a calm wave condition.

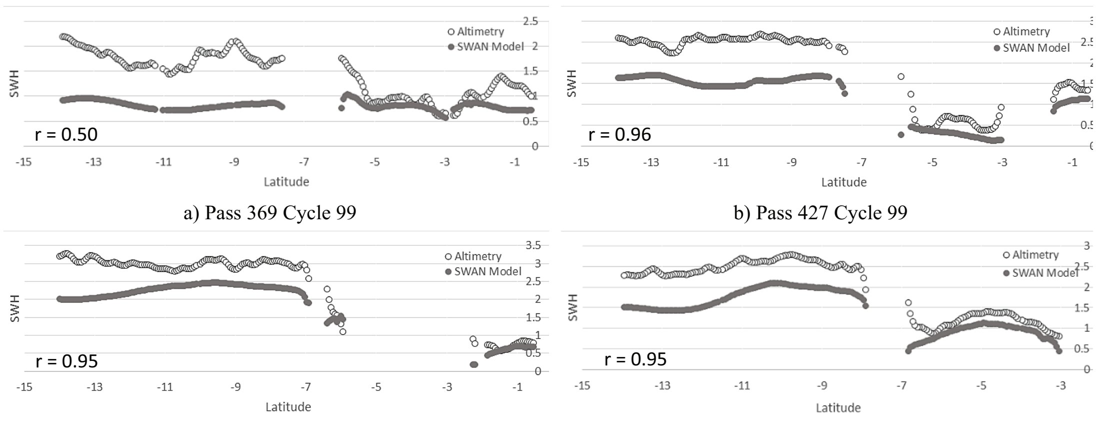
Modeling starts on 15 November 2017 at 00:00 to 5 December 2017 at 00:00 with computing every 1 hour.

3. Result and Discussions

3.1. Verification Results

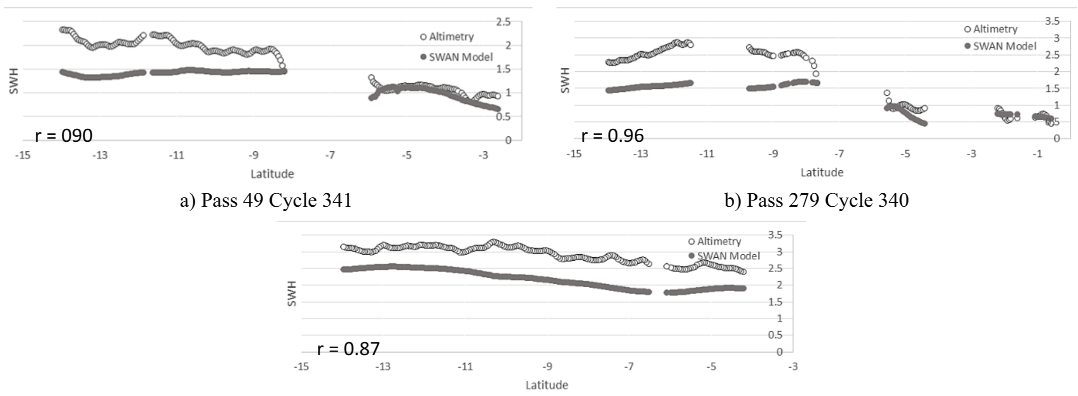
Modeling verification was carried out by performing a SWH comparison from SWAN modeling with SWH from the altimetry satellite in each satellite pass, then the correlation coefficient (r) between SWH modeling and SWH altimetry was calculated to determine the relationship of the two SWH data.

Based on the comparison results of SWH from SWAN modeling with SWH from altimetry satellite, all comparison charts show that SWH from modeling is under SWH from altimetry with the correlation coefficient (r) showing a strong relationship between the two data as shown in the Figure 2, Figure 3, Figure 4, and Figure 5.



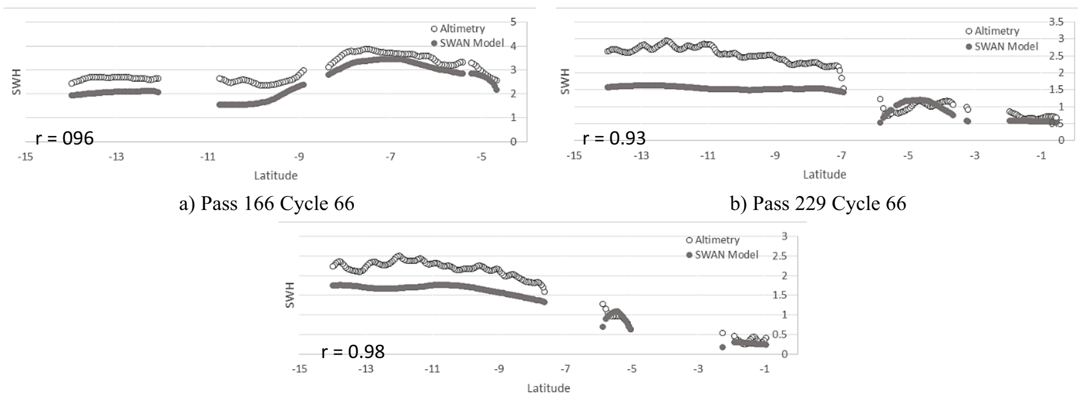
a) Pass 369 Cycle 99
b) Pass 427 Cycle 99
c) Pass 485 Cycle 99
d) Pass 528 Cycle 99

Figure 2: Modeling verification with Cryosat 2 Satellite.



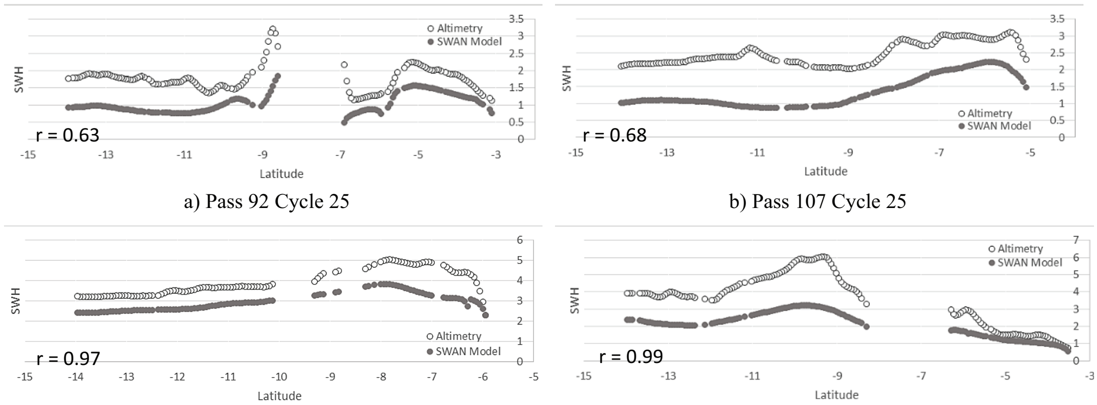
a) Pass 49 Cycle 341
b) Pass 279 Cycle 340
b) Pass 318 Cycle 340

Figure 3: Modeling Verification with Jason 2C Satellite.



a) Pass 166 Cycle 66
b) Pass 229 Cycle 66
b) Pass 249 Cycle 66

Figure 4: Modeling verification with Jason 3A Satellite.



a) Pass 92 Cycle 25

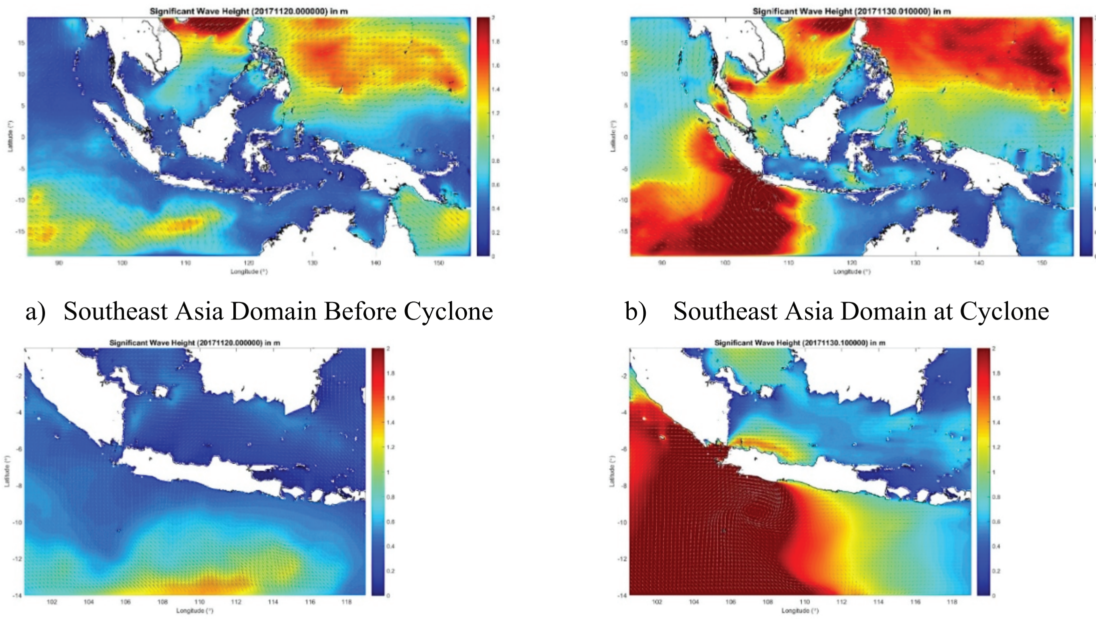
b) Pass 107 Cycle 25

c) Pass 178 Cycle 25

d) Pass 206 Cycle 25

Figure 5: Modeling verification with Sentinel 3A Satellite.

3.2. Modeling Result



a) Southeast Asia Domain Before Cyclone

b) Southeast Asia Domain at Cyclone

c) Lampung-Lombok Domain Before Cyclone

d) Lampung-Lombok Domain at Cyclone

Figure 6: Modelling result in Southeast Asia and Lampung -- Lombok Domain.

Based on Figure 6, there was a significant difference in wave height before the Cempaka-Dahlia Cyclone and during the cyclone. At the time before the Cempaka tropical cyclone and Dahlia occur in pictures (a) and (c), the waters in the Indian Ocean have a wave height between 0-1 meters. However, at the time when the Tropical Cyclone Cempaka and Dahlia the wave height increased up to >2 meters.

The results of modeling are also indicated by the SWH graph at the observation point and the percentage of SWH increase at observation points table are obtained by comparing the maximum wave height at the cyclone occurs against the average height of the wave height during normal conditions.

3.3. Modeling at Tourism Places

Observation points on tourism places in the study area are shown in the Figure 8. In Figure 7, it can be seen that there was a significant increase in wave height during the Cempaka and Dahlia tropical cyclones and decreased after the tropical cyclone ended. The observation points of Panaitan Island and Ujung Genteng Beach have increased wave heights up to 3.46 and 3.75 respectively. When viewed spatially, a significant increase in wave height occurs at the observation points in the southern regions of Central Java, West Java, Banten, and in the Sunda Strait. When viewed from Table 2, the largest percentage of SWH increase occurred on the island of Krakatau to reach 544.02% of normal conditions.

3.4. Modeling at Ports

Observation points on ports in the study area are shown in the Figure 9. The results of the SWH graph at the port observation point have similar results to the SWH grpah at the tourism place observation point where wave height increases occur during the Cempaka and Dahlia tropical cyclones. At the port observation point, the highest significant wave height during the cyclone occurred at Pelabuhan Ratu Port with a wave height of 2.09 meters, while at other observation points located in the northern part of Java Island and east of Java Island experienced only a slight increase in wave height as can be seen in Figure 10. This is also indicated by the percentage increase in SWH in Table 3. In Table 3, the highest percentage of SWH increase occurs in Pelabuhan Ratu Port with an increase of up to 1028.31% from normal conditions.

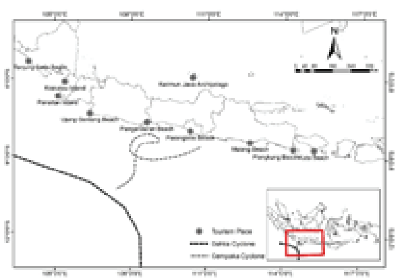


Figure 7: Tourism place observation points in study srea.

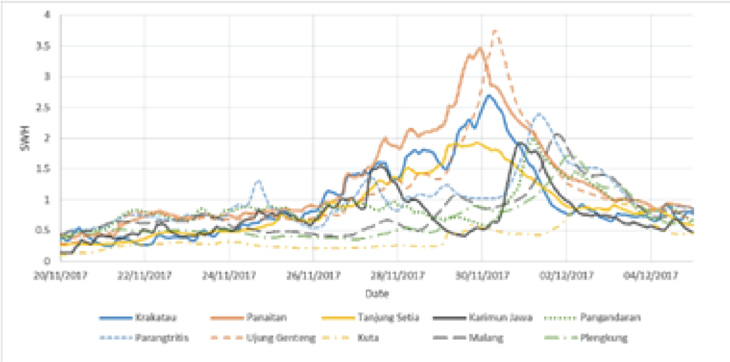


Figure 8: SWH graph at tourism place.

Table 2: Percentage of SWH increase at tourism places observation points.

Observation Points	Mean SWH at Normal Condition (m)	Max. SWH at Cyclone (m)	Percentage of SWH Increase
Krakatau Island	0.42	2.70	544.02
Panaitan Island	0.65	3.46	436.15
Tanjung Setia Beach	0.40	1.92	381.71
Karimun Jawa Archipelago	0.46	1.93	315.12
Pangandaran Beach	0.70	2.01	185.63
Parangtritis Beach	0.72	2.39	229.85
Ujung Genteng Beach	0.63	3.75	500.31
Kuta Beach	0.25	0.93	278.83
Malang Beach	0.60	2.06	245.74
Plengkung Beach	0.47	1.73	264.74

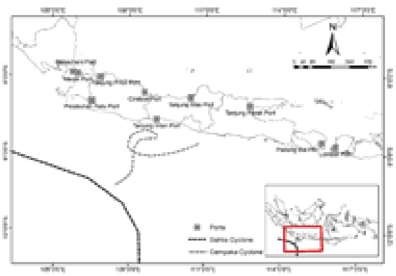


Figure 9: Ports Observation Points in Study Area.

3.5. Modeling at Power Plants

Observation points on power plants in the study area are shown in the **Figure 11**. Just as with the previous modeling results, at the observation points in power plants showed the results of a significant increase in wave height during the Cempaka tropical cyclone and Dahlia occurring with varying increases at each observation point. In the **Figure 12**, shows that the highest significant wave height occurs at Labuan Power Plant with wave

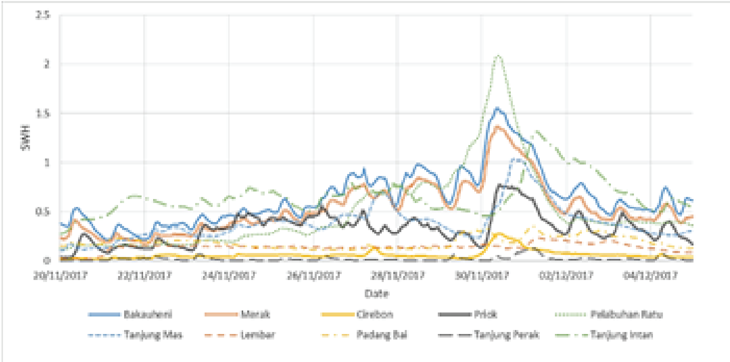


Figure 10: SWH graph at Ports.

TABLE 3: Percentage of SWH Increase at Ports Observation Points.

Observation Points	Mean SWH Before Cyclone	Max. SWH at Cyclone	Percentage of SWH Increase
Bakauheni	0.38	1.55	304.30
Merak	0.30	1.37	362.52
Cirebon	0.04	0.28	542.18
Tanjung Priok	0.23	0.78	241.80
Tanjung Intan	0.56	1.31	133.22
Pelabuhan Ratu	0.19	2.09	1028.31
Tanjung Mas	0.25	1.04	306.03
Lembar	0.12	0.23	86.45
Padang Bai	0.19	0.36	92.48
Tanjung Perak	0.02	0.13	84.62

height reaching 2.71 meters with a percentage increase of SWH reaching 909.97% as shown in the **Table 4**.

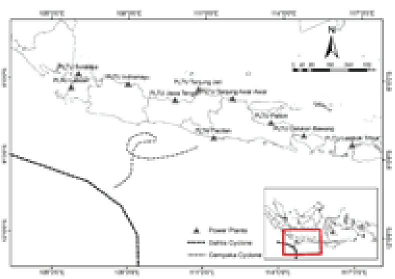


Figure 11: Power Plant Observation Points in Study Area.

Based on the modeling results, a significant increase in wave height at each observation point is spatially different. The highest increase in wave height occurs in the South and West regions of Java, especially in Central Java, West Java, Banten, and the Sunda Strait. This happens because the observation point in those areas is located close to the Tropical Cyclone Cempaka and Dahlia so that the impact of the cyclone is significant at

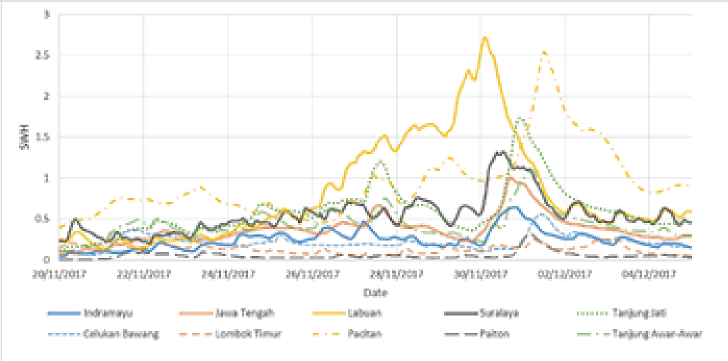


Figure 12: SWH graph at Power Plants.

Table 4: Percentage of SWH Increase at Power Plants Observation Points.

Observation Points	Mean SWH Before Cyclone	Max. SWH at Cyclone	Percentage of SWH Increase
Indramayu	0.16	0.64	312.85
Jawa Tengah	0.24	1.01	315.58
Labuan	0.27	2.71	909.97
Suralaya	0.35	1.32	277.73
Tanjung Jati	0.36	1.73	377.11
Celukan Bawang	0.21	0.56	164.63
Lombok Timur	0.17	0.26	52.05
Pacitan	0.67	2.55	277.36
Paiton	0.05	0.31	537.45
Tanjung Awar-Awar	0.35	1.10	214.66

the observation point at that place. At the observation point in the northern region of Java Island and the eastern part of Java Island, especially in Bali and Lombok, although the distance from the tropical cyclone is quite far, the increase in wave height due to Tropical Cyclones still occur. It can be seen in the SWH graph where there is an increase in wave height at the time of the Tropical Cyclone Cempaka and Dahlia although it is not as large as in the south of Central Java, West Java, Banten, and the Sunda Strait.

The wave height data from wave modeling can be used as a mitigation plan if a similar event occurs because the occurrence of tropical cyclones, in general, can be predicted by looking at the signs of tropical cyclone formation.

At several observation points, a significant increase in wave height reached > 300% from normal conditions. This can be a consideration in making policies related to safety and mitigation of high waves that might happen when other tropical cyclone phenomena occur. The response to high waves can vary depending on the place of coastal activity. In tourist attractions, a response can be made in the form of a ban on activities in the coastal areas, a prohibition on fishing or sailing for the port area and in a power plant that can be mitigated by installing breakwaters to secure assets and coal barges.

4. Conclusion

To sum up, the results of modeling verification are indicated by the correlation between the significant wave height from altimetry satellite and the significant wave height results from SWAN modeling which shows a high correlation. Meanwhile, significant wave height from SWAN modeling has a value below significant wave height of the altimetry satellite.

The SWAN modeling results at the observation point showed that the increase in wave height varied at each observation point, with the highest significant wave height at Ujung Genteng Beach as high as 3.75 m and the largest Percentage of SWH Increase at Observation Points at Pelabuhan Ratu Port with about 1028.31%.

Acknowledgements

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