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A 10-year wave energy resource assessment and trends of Indonesia based on satellite observations

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Abstract

Wave energy resource assessment and trends around Indonesian's ocean has been carried out by means of analyzing satellite observations. Wave energy flux or wave power can be approximated using parameterized sea states derived from satellite data. Unfortunately, only the surface parameters can be measured from remote sensing satellites, for example for ocean surface waves: significant wave height. Others, like peak wave period and energy period are not available, but can instead be estimated using empirical models. The results have been assessed by meteorological season. The assessment shows clearly where and when the wave power resource is promising around Indonesian's ocean. The most striking result was found from June to August, in which about 30–40 kW/m (the 90th percentile: 40–60 kW/m, the 99th percentile: 50–70 kW/m) wave power energy on average has been found around south of the Java Island. The significant trends of wave energy at the 95% level have also been studied and it is found that the trends only occurred for the extreme cases, which is the 99th percentile (i.e., highest 1%). Wave power energy could increase up to 150 W/m per year. The significant wave heights and wave power have been compared with the results obtained from global wave model hindcast carried out by wave model WAVEWATCH III. The comparisons indicated excellent agreements.

Key words: wave power energy, trends, ENVISAT altimeter, significant wave height, wave period

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1 Introduction

The national energy council of Indonesia reported that Indonesia energy demand would increase every year (Prasodjo et al. 2016). They projected that the energy price will increase in which the coal, gas, diesel oil and fuel oil, and biomass will increase up to 1.2%, 0.9%, 2.3% and 1.2%, respectively, per year. At the time of writing, the majority of electricity generation in Indonesia is from oil which mostly depends on foreign imports and thus depends on the oil price. For example, in 2015 the import ratio for the oil was about 44% which increased about 9% from 2007 where import ratio was 35% (Prasodjo et al. 2016).

In order to reduce such dependency, renewable energy has been considered. This consideration has been started in 2006 where Indonesian government stated explicitly in the presidential decree No. 5. Based on this decree, it is expected that renewable energy contribution will be 17% of total primary energy mix in 2025. From this figure, 5% should come from hydro-power which including ocean renewable energy such as ocean wave, ocean current and tidal energy. Other sources renewable energy are from biofuel (5%), geothermal (5%) and liquefied coal (2%). Recently, these figures have been revised by the Indonesia government regulation No. 79 in 2014. In this new regulation, the expectation from the renewable energy has been increased from 17% to 23% in 2025. Moreover, the government also has put an

other target in 2050 in which 31% of total energy mix should come from renewable energy. In order to achieve such targets, assessments on renewable energy should pay more attentions particularly for ocean renewable energy which has not been really explored.

Since Indonesia is an archipelago country that has more ocean than land, i.e., 64.97%, it has a great potential of wave energy resources (Mudho, 2011) as well as tidal energy (Ribal et al. 2017; Purnamasari et al., 2018). This is also supported by the Agency for the Assessment and Application of Technology, Indonesia which found that Indonesia has relatively high ocean wave energy potential especially in the region of west of Sumatera, south of Java, Bali, West Nusa Tenggara and East Nusa Tenggara (BPPT, 2014). Therefore, it is a great of importance to assess the wave energy potential in more intensive manner.

Recently, Ribal and Zieger (2016) have done a preliminary assessment of wave energy resources around Indonesia by analyzing the calibrated ENVISAT data. However, their assessment was limited to two years period which are from 2010 until 2011. Their results are in a good agreement with the data obtained from global wave model (Ardhuin et al., 2010; Durrant et al., 2014; Hemer et al., 2017).

In the present paper, we will extend the work of Ribal and Zieger (2016) by using ENVISAT altimeter data over the full peri-

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od from 2002 to 2012. In addition, the trends in wave energy at the 95% level will be studied and a seasonal assessment is given which beyond the work of Ribal and Zieger (2016). Moreover, the results based on the altimeter observations will be compared with the 10³⁷ hindcast of global wave model carried out by well-known wave model WAVEWATCH III version 4.08 (Tolman, 2009; Ardhuin et al., 2010; Durrant et al., 2014).

The structure of this paper is as follows. The description of the calibrated ENVISAT altimeter data will be described in Section 2 following by mean significant wave height and peak period in Section 3. Wave power energy potential in Indonesia as well as its trends over the ENVISAT observations will be presented in Sections 4 and 5, respectively. The comparison with the results obtained from global wave model WAVEWATCH III will be shown in Section 6 following the conclusions in Section 7.

2 ENVISAT altimeter data

The European Space Agency (ESA) launched many missions including ERS1 (European Remote sensing Satellite), ERS2 and ENVISAT altimeter. The later satellite was launched on March 1, 2002 in French Guiana. This satellite was operated for 10 years, which is from 2002 to 2012. The main purpose of the ENVISAT mission was to monitor land, ocean, atmosphere and ice (Zieger, 2010). Moreover, ENVISAT altimeter has some similarities with ERS2 where both satellites have the same exact repeat mission (ERM) which is 35 d, inclination (98.54°), altitude (784 km) and size of footprint (Quarty et al., 2001; Zieger, 2010). All data over the duration of this satellite observation will be used in this present work where the calibrated data is available from Globwave database, <http://globwave.ifremer.fr/> (Queffelec and Croize-Hillon, 2012). Moreover, the validation and the quality control procedure that have been used in Zieger et al. (2009) (also see Zieger, 2010; Young et al., 2011; Zieger et al., 2014; Babanin et al., 2014a, b), will also be applied here to obtain the significant wave height and Ku-band radar altimeter backscatter for our need. Furthermore, the data have been binned to a resolution of 1°×1° which represents the optimal resolution for continuous global coverage based on the characteristic geometry of altimeter ground tracks (Zieger, 2010; Vinoth and Young, 2011).

3 Significant wave height and peak wave period

The significant wave height is one of the most important parameters in assessing wave energy resources. This parameter is available in the ENVISAT and it can be extracted in the straightforward manner. Another parameter in estimating wave power energy is peak wave period. The details of these two parameters will be presented in the following two subsections.

3.1 Mean significant wave height

As aforementioned, significant wave height parameter is recorded in the ENVISAT which can be extracted in straightforward manner. As a result, mean value of the significant wave heights for each month or years can be documented. Hence, mean significant wave height based on ENVISAT altimeter mission for ten years is presented in Fig. 1. As shown in the figure, the highest mean wave height during the observation time can be found in the south of the Java Island, southwest of the Sumatera Island, south of Bali and south of West Nusa Tenggara as well as East Nusa Tenggara where mean significant wave height is more than 2 m. It should be noted that since this is the mean of significant wave height, some individual waves could be more or less than the significant wave height. Unfortunately, the figure can only give the general picture of the location in which the significant

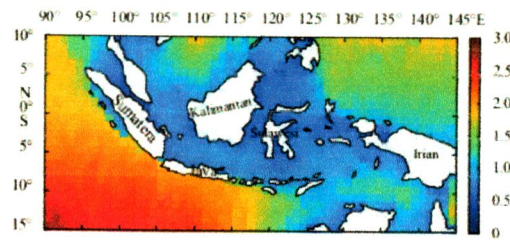


Fig. 1. Mean significant wave height (m) from 2002 until 2012.

ant wave heights are high that is our interest.

In order to obtain more detail information about the time in which mean significant wave heights are very high in some locations in Indonesia, then period of time has been classified into four different seasons based on the meteorological season, namely December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). Mean significant wave heights for each season during ten-year observations are shown in Figs 2–5, respectively.

Figure 2 shows mean significant wave heights during ten years satellite observation for three months which are from December until February each year in which rainy season in Indonesia. During this period of time, mean significant wave heights around south of Java and southwest of Sumatra have almost similar to the wave heights around north of Irian which are about 2 m. It should be noted that during these three months period, winter in the northern hemisphere and summer in the southern hemisphere. Interestingly, mean significant wave heights between March and May and between September and November are similar in which mean significant wave heights are less than three meters. These results were presented in Figs 3 and 5, respectively. The most striking significant wave height occurred from June to August every year where the highest mean significant wave height occurred at this time as shown in Fig. 4.

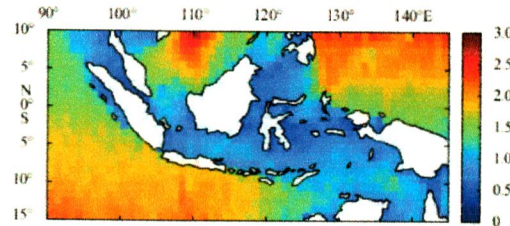


Fig. 2. Mean significant wave heights (m) from December to February (DJF) between 2002 and 2012.

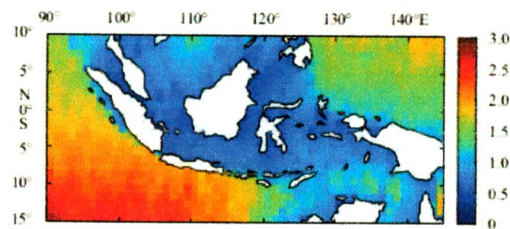


Fig. 3. Mean significant wave heights (m) from March to May (MAM) between 2002 and 2012.

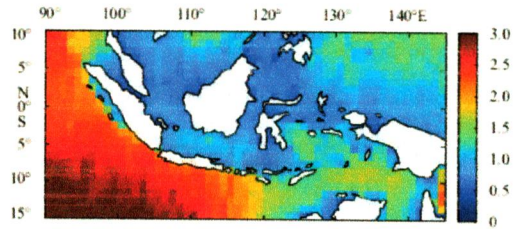


Fig. 4. Mean significant wave heights (m) from June to August (JJA) between 2002 and 2012.

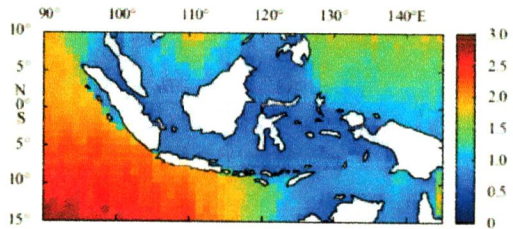


Fig. 5. Mean significant wave heights (m) from September to November (SON) between 2002 and 2012.

In fact, mean wave heights could reach up to more than 3 m at some locations. These results give us the idea of wave power energy in which the higher the significant wave height, the higher the wave power energy.

3.2 Mean peak wave period

As a matter of fact, from all parameters recorder in ENVISAT altimeter, none of them is the peak period or in other words, it should be mentioned that peak period parameter is not available from ENVISAT altimeter. Fortunately, Gommenginger et al. (2003) (also see Gommenginger et al., 2004, 2005), has proposed a simple empirical model to estimate peak wave period (T_p) based on Ku-band radar altimeter backscatter (σ^0) and the significant wave height (H_s). Their model was based on co-located TOPEX buoy measurements that is

$$\log_{10} T_p = 0.154 + 1.797 \times \log_{10} X \quad (1)$$

where $X = (\sigma^0 \times H_s^2)^{0.25}$. Moreover, Gommenginger et al. (2003) concluded that wave period can be estimated globally with an accuracy of 0.8 s root-mean-square error. In addition, Zieger et al. (2009) also found that ENVISAT derive wave height on the other hand was found to be within 0.156 m accurate (root-mean-square error) when compared to selected buoys.

Applying Eq. (1) by utilizing significant wave heights and Ku-band radar altimeter backscatters, mean wave periods for a decade are revealed in Fig. 6. As shown in the figure, all mean peak periods are less than 12 s and interestingly mean peak period has similar patterns to the significant wave height. Following a similar fashion to the significant wave height, mean peak period is also classified into four seasons as shown in Figs 7-10, respectively.

4 Wave power energy potential in Indonesia

Following the procedure that has been used by Ribal and Zieger (2016) at least two parameters have to be specified in or

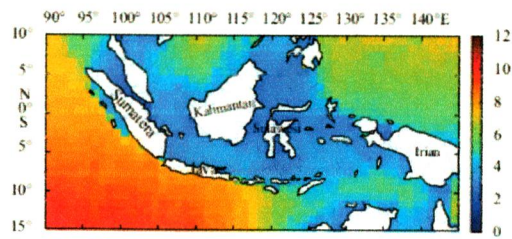


Fig. 6. Mean peak wave period (s) from 2002 until 2012.

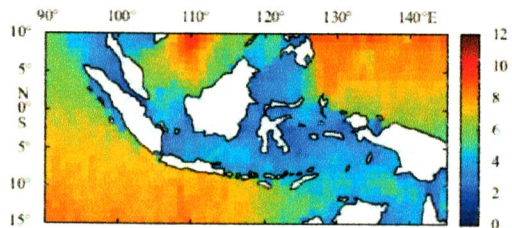


Fig. 7. Mean peak wave period (s) from December to February (DJF) between 2002 and 2012.

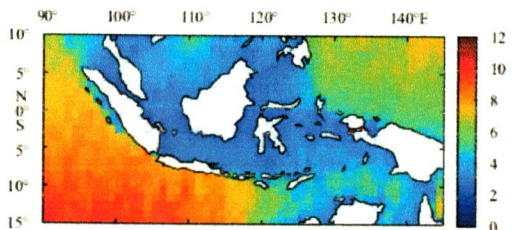


Fig. 8. Mean peak wave period (s) from March to May (MAM) between 2002 and 2012.

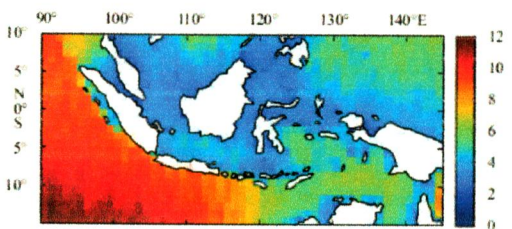


Fig. 9. Mean peak wave period (s) from June to August (JJA) between 2002 and 2012.

der to estimate the wave power energy namely significant wave height (H_s) and wave energy period (T_e). However, as has been pointed out by some researchers such as Cornett (2008), the later parameter is rarely specified. As a consequence, this parameter has to be estimated from other variables when information about the wave spectra is unknown. Cornett (2008) reported that if the peak period is known, then relation between wave energy period and peak period is given by $T_e = \alpha T_p$, e. then, used $\alpha = 0.90$ or $T_e = 0.9 T_p$ in his work by arguing that it is equivalent to assuming a standard JONSWAP spectrum with a peak enhancement factor of $\gamma = 3.3$. Recently, IEC (International Electrotechnical Commission)

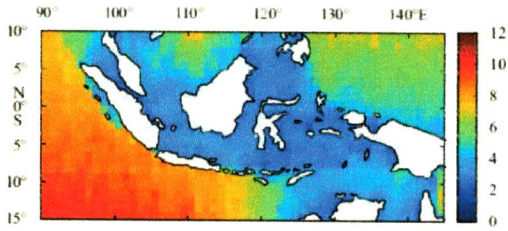


Fig. 10. Mean peak wave period (s) from September to November (SON) between 2002 and 2012.

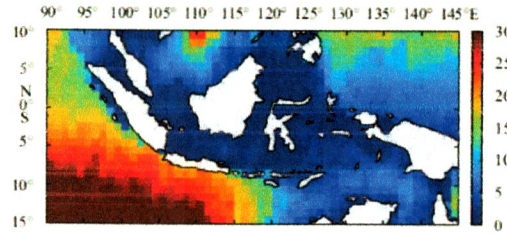


Fig. 11. Mean wave power (kW/m) estimated from altimeter from 2002 and 2012.

(Peacock, 2015) improved the ratio between wave energy period and peak wave period to 0.857 that is $T_e = 0.857 T_p$. However, for simplicity, Hagerman (2001) used wave energy period is the same as peak wave period, e.g., $T_e = T_p$. Following this approach, we choose to represent wave energy period with the peak wave period.

Using parametrized sea states and assuming deep water as also applied by some researchers such as Pontes (1998) and Zheng et al. (2013) (also see Wan et al. (2016) and the references therein) wave energy density, P (W/m), can be estimated by

$$P = \frac{\rho g^2}{64\pi} H_s^3 T_e \quad (2)$$

where ρ is the water density ($\sim 1027 \text{ kg/m}^3$), g is the gravity acceleration, and H_s is the significant wave height. Again, we assumed that $T_e = T_p$ and hence, wave energy density (kW/m) is approximated by

$$P = 0.5 H_s^3 T_p \quad (3)$$

It is clearly seen from Eq. (3) that errors of wave power are highly contributed from errors of significant wave height than wave period. This is because wave power energy is proportional to the significant wave height squared. Furthermore, the estimated wave power energy throughout Indonesia for ten years will be presented in the following subsections.

4.1 A decade of mean wave power energy

As aforementioned, the highly correlated parameter for wave power energy assessment is the significant wave height. As a result, the pattern of the wave power is similar to the pattern of the significant wave height. In fact, the most promising wave power energy along Indonesia archipelago is similar to the place where significant wave height is also high after applying Eq. (3). Hence, as shown in Fig. 11, the highest wave power is located in the south of the Java Island, south of Bali, south of West Nusa Tenggara as well as East Nusa Tenggara. Another location is around, southwest of the Sumatera Island, particularly for some small islands such as the Simeulu Island, Nias Island and Siberut Island. In these locations, the wave power can be obtained up to 30 kW/m. In addition, wave power with highest 10% or the 90th percentile is also calculated as shown in Fig. 12. It is clear seen from the figure that the wave power is about 30-50 kW/m. Moreover, wave power in the extreme conditions as depicted in Fig. 13 gives wave power about 40-60 kW/m. Again, mean wave power has also been classified into four seasons in order to observe more details of wave power that will be presented in the following subsection.

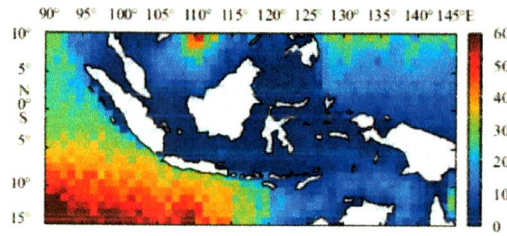


Fig. 12. The 90th percentile wave power (kW/m) estimated from altimeter from 2002 and 2012.

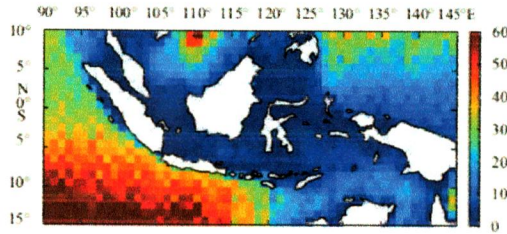


Fig. 13. The 99th percentile wave power (kW/m) estimated from altimeter from 2002 and 2012.

4.2 Seasonal wave power energy resources

By looking at four different seasons for significant wave height as well as peak wave period, one can identify key seasons for wave power energy. Similar to the significant wave height, wave power energy is very weak from December to January every year. In fact, less than 25 kW/m of wave power energy were found from locations which are located in the south of the Java Island, southwest of the Sumatera Island, south of Bali, south of West Nusa Tenggara and also East Nusa Tenggara as shown in Fig. 14. Wave power energy in between March and May as well as between September and November are similar where wave power can be expected up to 30 kW/m as presented in Figs. 15 and 16, respectively. Unlike other three seasons, Fig. 17 depicts the most promising season from harvesting wave power energy where more than 30 kW/m can be obtained during the season. The highest 10% or the 90th percentile of wave power have also been estimated and we found that more than 40 kW/m can be gained from this season. Moreover, the highest 1% or the 99th percentile, which is for extreme events, gives more than 50 kW/m during this season which is from June until August. Figures for the 90th and the 99th percentiles are not presented from simplicity.

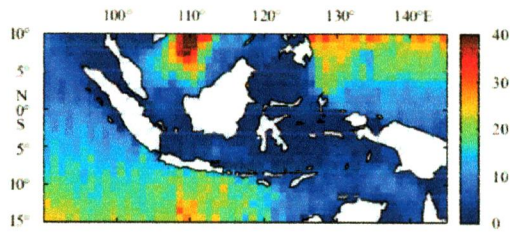


Fig. 14. Mean wave power (kW/m) from December to February (DJF) between 2002 and 2012.

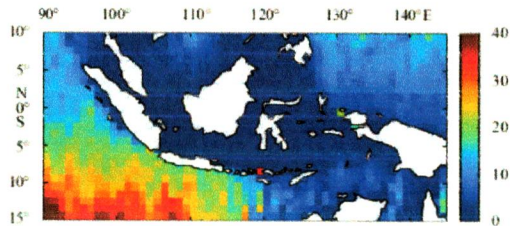


Fig. 15. Mean wave power (kW/m) from March to May (MAM) between 2002 and 2012.

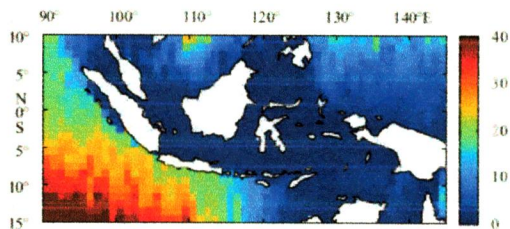


Fig. 16. Mean wave power (kW/m) from September to November (SON) between 2002 and 2012.

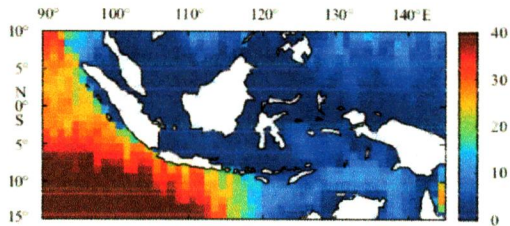


Fig. 17. Mean wave power (kW/m) from June to August (JJA) between 2002 and 2012.

5 Wave power energy trends for 10 years

Another important consideration for this study is to estimate the slope of the linear trends at the 95% level of the wave power over the entire duration of the ENVISAT mission based on the Mann-Kendall test. This test is a nonparametric test (Mann, 1943; Kendall, 1955; Sen, 1968) of randomness against a trend which is robust against outliers and missing data (Young et al., 2011; Zieger et al., 2014). The magnitude of trend can be estimated from Kendall's rank correlations (Sen, 1968). The effect of auto-correlation was taken into account (Young et al., 2011; Zieger et

al., 2014). The Mann-Kendall test statistic depends on the auto-correlation which would increase the apparent level of significance if the correlation is positive and vice versa. For each grid box the Mann-Kendall test has been applied to estimate trends. The trends of wave power energy and the 99th percentile are presented in Figs 18 and 19 respectively. The dots on the figures depict the significant trends of wave power at the location at the 95% level. As seen, Fig. 18 does not have any dots which means that wave power for ten years does not have any trends at the 95% level which indicates that during the period of time, the wave power is relatively steady. In addition, the magnitude of the trends shown in Fig. 20 are very small. However, for the 99th percentile, the trends of wave power do occur in some areas as shown in Fig. 19 and their slopes are presented in Fig. 21. It should also be mentioned that the trends for the extreme case are not uniform in time and space which indicates that both increase and decrease in mean wave power depending on the location. In addition, the trends of the significant wave heights have also been estimated and it is consistent with the results obtained by Zieger (2010).

6 Comparison to global wave model

In order to compare our result with respect to the global wave model, we will use the data obtained from global wave model hindcast that have been done using WAVEWATCH III wave mod-

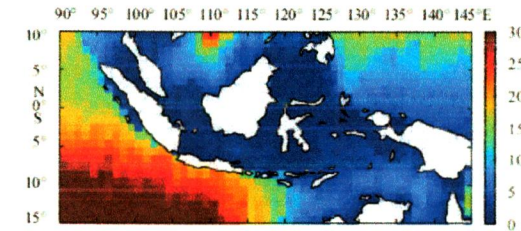


Fig. 18. Mean wave power (kW/m) and its significant trends (dots) from 2002 to 2012.

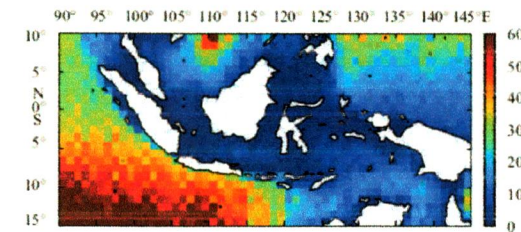


Fig. 19. The 99th percentile of mean wave power (kW/m) and its significant trends (dots) from 2002 to 2012.

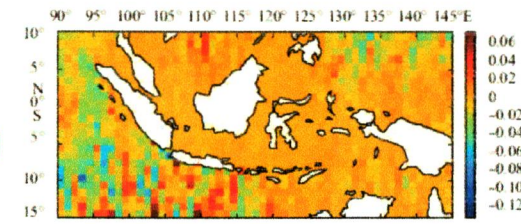


Fig. 20. Mean wave power trend from 2002 to 2012.

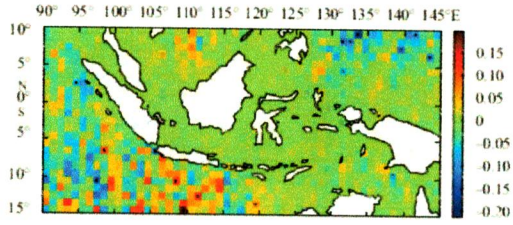


Fig. 21 The 99th percentile of mean wave power trend from 2002 to 2012.

el Version 4.08. These simulations have been carried out by Durant et al. (2014) for a duration of more than 30 years, which are from 1979 to 2013 (http://opendap.bom.gov.au:8080/thredds/catalog/paccsapwaves_gridded/catalog.html, accessed on March 29, 2018). For global coverage, the hindcast resolution is 0.4°. In order to perform the comparisons for significant wave heights and wave power between model and altimeter, we were inspired by the method used by Raschle et al. (2008) in which we compare between the average data along the satellite track and the interpolated model data with respect to the satellite track over 1° latitude steps. However, in this work, we use the number of data average which are greater or equal to 14 instead of 12 that have been used by the previous authors. Four different statistical parameters, namely bias (B), root mean square error (RMSE), Pearson's correlation coefficient (ρ) and scatter index (SI) will be used. The comparison between model (M) and altimeter (A) are carried out by using the following equations where N is the number of points used (Zieger et al., 2015).

$$B = \frac{1}{N} \sum_{i=1}^N (M_i - A_i) \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - A_i)^2} \quad (5)$$

$$\rho = \frac{\text{cov}(M, A)}{\sqrt{\text{cov}(M) \text{cov}(A)}} \quad (6)$$

$$SI = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - A_i - B)^2}}{\frac{1}{N} \sum_{i=1}^N A_i} \quad (7)$$

The summary of the comparisons presented in the following Table 1 and the scatter density for significant wave heights and wave power are presented in Figs 22 and 23, respectively.

In general, as can be seen from the table, the significant wave heights from altimeter and the global wave model are in an excellent agreement. In fact, RMSE for ten years comparison is 0.288 m and the correlation coefficient is 0.941. The scatter index is very small, that is 0.167 and bias is negative which is -0.092 m. The number of points used for the significant wave heights comparison between the model and altimeter are 98 385.

Although the wave power from ENVISAT altimeter and WAVEWATCH III wave model is less accuracy compared to the significant wave heights, the results are also still acceptable where bias, root mean square error, Pearson's correlation coefficient and scatter index are -0.414 kW/m, 5.640 kW/m, 0.816 and 0.608, respectively. This small discrepancy could be caused by many things in which one of them is the choice of peak period and is the same as peak wave energy.

7 Conclusions

Wave energy resource assessment and trends around Indonesian's ocean has been carried out by means of analyzing satellite observations and utilizing all over the 10-year ENVISAT mission (2002-2012). The results have been analyzed by season. The highest wave power was found in JJA season (June to August), in which about 30-40 kW/m (the 90th percentile 40-60 kW/m, the 99th percentile 50-70 kW/m) on average is expected around south of the Java Island, south of Bali, south of West Nusa Tenggara and also East Nusa Tenggara. Other locations, which are also promising, are around southwest of the Sumatera Island particularly for some small islands such as the Simeulue Island, Nias Island and Siberut Island. The significant wave heights and wave power obtained from altimeter have been compared relative to the results obtained from global wave model WAVEWATCH III. It is found that the results are in excellent agreements.

Table 1. Model ENVISAT comparisons for significant wave height (H_s, measured in m) and wave power (P measured in kW/m by year) and for entirely 10 years

Period	N		B		RMSE		ρ		SI	
	H _s	P	H _s	P	H _s	P	H _s	P	H _s	P
2002	5 590	2 991	-0.049	-0.285	0.375	5.131	0.900	0.834	0.231	0.602
2003	9 740	5 466	0.115	-0.932	0.283	6.305	0.945	0.810	0.159	0.649
2004	10 059	5 610	-0.112	-0.924	0.268	5.561	0.950	0.838	0.149	0.563
2005	9 930	5 357	0.116	-0.568	0.290	5.304	0.946	0.831	0.163	0.591
2006	9 932	5 394	-0.079	-0.600	0.272	5.530	0.945	0.828	0.158	0.579
2007	9 675	5 190	-0.076	-0.125	0.284	5.642	0.941	0.819	0.168	0.611
2008	10 181	5 317	0.093	-0.479	0.275	5.647	0.948	0.827	0.156	0.586
2009	10 362	5 759	-0.096	-0.292	0.282	5.554	0.943	0.811	0.166	0.620
2010	9 617	5 202	-0.108	-0.261	0.288	5.662	0.943	0.815	0.167	0.626
2011	10 583	5 611	-0.064	+0.317	0.290	5.729	0.937	0.777	0.173	0.645
2012	2 716	1 502	-0.079	-0.148	0.282	5.758	0.951	0.804	0.161	0.564
2002-2012	98 385	51 999	-0.092	-0.414	0.288	5.640	0.941	0.816	0.167	0.608

Note: The comparisons include the number of points (N), bias (B), root mean square error (RMSE), Pearson's correlation coefficient (ρ) and scatter index (SI).

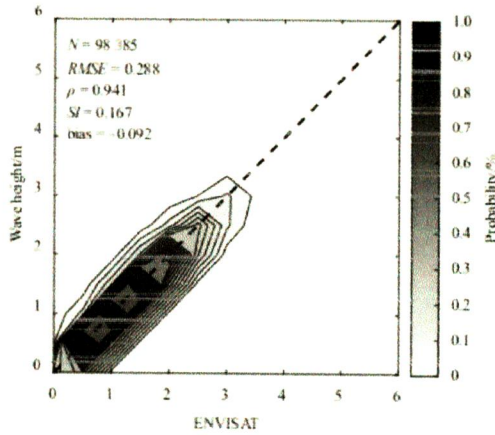


Fig. 22. Comparison of modelled significant wave height relative to observations from ENVISAT altimeter

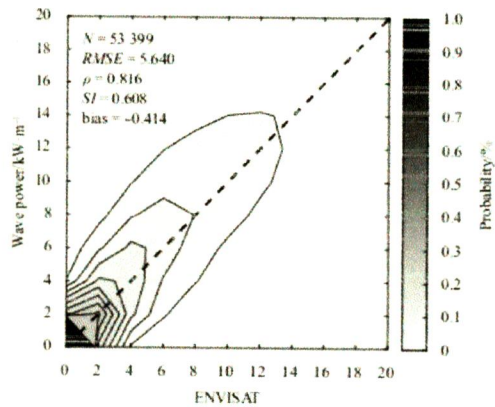


Fig. 23. Comparison of modelled wave power relative to observations from ENVISAT altimeter

These results are not only beneficial for wave energy interest but they are also useful information for constructing offshore infrastructures such as oil explorations. Moreover, it also can give some ideas for Indonesia government to consider harvesting wave energy in some small islands such as the Simeulue Island, Nias Island and Siberut Island instead of obtaining the electricity from main island of Sumatera.

Since ENVISAT altimeter retired in 2012, if one is interested in approximating wave power energy after 2012, then they could use the data from other satellites such as JASON-2, JASON-3, SARAL (Satellite with ARGOS and ALtiKa), Sentinel-3A, CRYOSAT-2 and Hai Yang 2 (HY-2) which is China's first dynamic environmental satellite. Although the data from satellites have been proven highly accuracy, the resolution is very coarse as the optimum gridded is one degree. Therefore, for future work, it will be good to utilize ocean global model as well as coastal model to assess wave power energy such as WAVEWATCH III and SWAN (Simulating WAVes Nearshore) to achieve high-resolution wave-power energy assessment.

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