Assessment of wave energy potential along the south coast of Java Island

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Abstract. The south coast of Java Island has a great potential for wave energy. A long-term analysis of a 10-year wave dataset obtained from the ERA-Interim database is performed for preliminary wave energy assessment in this area, and it was seen that the annual median power is expected to exceed 20kW/m along the coast. A coastal wave model with an unstructured grid was run to reveal the wave conditions and to assess the wave energy potential along the coast in detail. The effect of swells and local wind on the wave conditions is investigated. Annual median wave power, water depth and distance from the coast are selected as criteria for the identification of suitable locations for wave energy conversion. Two zones within the study area emerge to be suitable for wave energy extraction. Swells from the southwest turned out to be the major source of wave energy and highest monthly median wave power reached about 33kW/m.

1. Introduction
Wave energy has recently become the interest of many researchers around the world. Several studies on global wave resource based on the data obtained from global wave models such as ECMWF (European Centre for Medium-Range Weather Forecasts) and NWW3 (National Oceanic and Atmospheric Administration WAVEWATCH III) reveal that higher wave heights are more likely to appear on the east coast of oceans in both hemispheres [1]. Based on the wave energy atlas [1], the highest power for primary swell appears off the western Australian coast, reaching an average of 60kW/m during the winter months of the southern hemisphere. Since the main direction of these swell are northeast, they reach the Java Island with considerable wave energy. Another advantage of exploiting the wave energy in this area is that the seasonal variation of wave conditions is much lower than in most areas of the Northern Hemisphere [2]. Thus, wave converters can give more stable output power throughout the year and the lower appearance of extreme conditions can reduce the costs of wave projects.

Site selection for the installation of wave energy devices depends on available power, site characteristics, and possible environmental and socio-economic impacts of the projects. However, wave conditions are still decisive criteria [3]. Several studies have successfully applied wave models to assess the wave energy potential at different locations in Europe and North America utilizing the
wave data covering around 10 years from WAM or WAVEWATCH III to analyze the long-term wave variability and to roughly estimate exploitable wave energy [4], [5], [6], [7]. Coastal wave models with refined computational grids and more accurate bathymetric data were also put in progress to determine optimum locations for a wave farm. In this study, results of an assessment of the wave conditions and the wave energy potential in the south coast of Java Island are presented.

2. Methodology and application

Within the investigated domain in this study, waves produced in the Indian Ocean spreading to the south coast of Java Island, and local winds, as a part of the monsoon system, are main sources of wave energy. Therefore, different wave systems due to swell and local winds can be expected, and separate parameters for the wave systems allow estimation of the power from the dominant wave components using respective peak periods. Thus, precise information can be provided for planning and design of wave farms [1]. The year-to-year variability of the wave conditions is revealed by long-term analysis. After that, the detailed seasonal variations and the wave energy in coastal area are presented through wave simulations.

Figure 1. Study domain with bathymetry and locations of satellite tracks, wave buoy station and long-term analysis points.

Figure 2. Unstructured grid of CWM in the computational domain.

The ERA-Interim dataset from ECMWF is chosen for the long-term wave analysis. It provides 6-hourly values on significant wave height, mean wave period and wave direction [8]. The wave conditions in deep water along the coast using wave data covering 10 years (2004-2014) are analyzed to roughly evaluate the wave potential in down-wave directions. For the analysis, 18 points with
constant distances along the 2000m isobath line off the coast are selected (Figure 1). Besides, the wave data from ERA-Interim are also utilized to drive the coastal wave model.

Numerical wave simulations are performed with SWAN (Simulating Waves Nearshore) [9] to reveal detailed wave conditions near the coast. An unstructured triangle grid is constructed and applied to keep the high resolution in the coastal area, and avoiding unnecessary computation resource cost in deep water (Figure 2). The coarsest meshes are on the open boundary matching the grid of the ERA-Interim dataset with a resolution around 14km, while the finest meshes are off the coast with an average resolution of about 500m. The criteria based on a 2D spectrum, which have been used also in WAM, are implemented in SWAN for the wind-swell-wave identification [10].

Coastal wave model (CWM) is validated based on both wave buoy and satellite data. Location of the wave buoy, which generates raw north, west and vertical displacements at a rate of 1.28 Hz, is indicated in Figure 1. Figure 3a and Figure 3b show the comparisons of significant wave height and mean wave period between CWM and buoy observations, and the comparison of significant wave height due to swell (Hs swell) and local wind (Hs wind) can be seen in Figure 3c and Figure 3d. Figure 3c and Figure 3d also reveal that the main wave energy comes from swells at the location of the buoy.

![Figure 3. Comparison of time series between CWM and buoy: (a) significant wave height; (b) mean wave period; (c) significant wave height due to swells; (d) significant wave height due to local winds.](image-url)
Figure 4. Significant wave height scatter plot of CWM (coastal wave model) versus altimetry data from Jason-2: (a) rainy season; (b) dry season

The altimeter data from Jason-2, provided by AVISO (Achieving Validation and Interpolation of Satellite Oceanographic Data), is also employed to validate the model due to lack of in-situ wave measurements along the south coast of Java Island. The dataset contains significant wave height only. The measurement interval at one sub-satellite point is about 10 days. The locations of sub-satellite points on 8 passes in the model domain are showed in Figure 1. Figure 4a and Figure 4b show significant wave height scatter plot of CWM versus altimetry data from Jason-2. The figures show that CWM has a better agreement with altimetry data in the dry season (2014/5 to 2014/10) than in the rainy season (2013/11 to 2014/04). It is seen that the difference of significant wave height between CWM and the altimetry data are usually smaller than 0.5m.

Figure 5. 2D spectrum comparison between CWM and buoy: (a, c) buoy; (b, d) CWM.
Figure 5a-d reveals that swells dominate the wave field both in extreme wave condition (Figure 5a, Figure 5b) and the average wave condition (Figure 5c, Figure 5d). Primary swells in two time points (S1, S2 in Figure 3a) are from different directions. In the southern hemisphere, the strong westerlies result in heightened wave activities in mid-latitude throughout the year and those waves combine with the trade wind waves when propagate to north [1]. This fact implies that the southwesterly primary swell in the extreme wave condition is due to the westerlies while the southeasterly primary swell in the average wave condition is due to the trade wind.

3. Characterization of wave energy potential in the study area

Based on the 10-year wave data from the 18 points along the 2000m isobath line off the coast, Mean significant wave height is about 2.04m and the mean wave period is about 10.69s. The inter-annual variation of these two wave parameters is small. In addition, significant wave height in dry seasons is higher than in rainy seasons with a mean difference of about 0.43m. Furthermore, mean wave period in dry seasons is approximately 0.4s higher than rainy seasons. Since the points for the analysis are located in deep waters, mean annual median wave power can be estimated with the wave statistic parameters as follows:

$$P = \frac{\rho g^2 H_s^2 T_{m01}}{64\pi}$$

(1)

where \(\rho\) is water density, \(g\) is gravitational acceleration, \(H_s\) is significant wave height, \(T_{m01}\) is mean wave period. Estimated mean annual median wave power based on Eq. (1) is 22kW/m, while required annual median wave power for most commercial wave energy converters is around 20kW/m [2]. The seasonal variation of wave power in this area is insignificant. In rainy seasons, the seasonal median wave power reaches 17kW/m and in dry seasons, the seasonal median wave power is 27kW/m (Table. 1).

| year | Hs (m) | Tm01 (s) | Power (kW/m) |
|------|--------|----------|--------------|
|      | An.    | dry      | rainy        | An. | dry | rainy |
| 04-05 | 2.08   | 2.29     | 1.87         | 11.0 | 11.2 | 10.9  | 23.5 | 28.9 | 18.7 |
| 05-06 | 2.13   | 2.33     | 1.93         | 10.9 | 11.1 | 10.8  | 24.5 | 29.7 | 19.8 |
| 06-07 | 2.08   | 2.33     | 1.83         | 10.8 | 11.1 | 10.6  | 23.0 | 29.5 | 17.3 |
| 07-08 | 2.10   | 2.28     | 1.91         | 10.6 | 10.8 | 10.4  | 22.9 | 27.7 | 18.7 |
| 08-09 | 2.05   | 2.25     | 1.85         | 10.7 | 11.0 | 10.4  | 22.0 | 27.3 | 17.5 |
| 09-10 | 1.89   | 2.14     | 1.64         | 10.5 | 10.8 | 10.3  | 18.5 | 24.3 | 13.7 |
| 10-11 | 1.98   | 2.13     | 1.84         | 10.3 | 10.6 | 10.0  | 19.9 | 23.6 | 16.6 |
| 11-12 | 2.02   | 2.19     | 1.85         | 10.4 | 10.5 | 10.3  | 20.9 | 24.9 | 17.4 |
| 12-13 | 2.07   | 2.28     | 1.85         | 10.8 | 10.9 | 10.6  | 22.7 | 27.9 | 17.9 |
| 13-14 | 2.04   | 2.34     | 1.74         | 10.8 | 10.9 | 10.7  | 22.2 | 29.4 | 16.0 |
| mean  | 2.04   | 2.26     | 1.83         | 10.7 | 10.9 | 10.5  | 22.0 | 27.3 | 17.4 |

Detailed information of wave conditions in the coastal area are based on the results from CWM. Wave power calculations are made using equation:
\[ P = \int_0^{2\pi} \int_{f_{\text{min}}}^{f_{\text{max}}} \rho g c_g E(\theta, f) df d\theta \]  

(2)

where \( P \) is the wave power, \( c_g \) is the wave group speed and \( E(\theta, f) \) is the power density as a function of the wave direction (\( \theta \)) and frequency (\( f \)).

Monthly median significant wave height, mean wave period and wave power within 30 nautical miles off the coast are estimated. Swells provide the majority of wave energy (Figure 6a), while mild local winds of speed about 3-5m/s does not play an important role on wave conditions through the year. The average monthly median wave power for swells is estimated as 15kW/m from November 2013 to April 2014, and 25kW/m from May 2014 to October 2014. Meanwhile, the wave power for winds is less than 1kW/m through the year and varies with the wind speed and direction. With the dominance of the swells, significant wave height in the dry season is higher than in the rainy season. The mean wave period in this area is around 6s-8s through the year. The stronger swells in dry season result in the larger mean wave period of around 8s. The peak wave power appears in August 2014 during the period. The detailed information in that month is provided by Figure 7. In August 2014, the monthly median wave power of more than 30kw/m is mainly from the southerly swells. The local winds from southeast only provide the wave power of 0.9kw/m.

**Figure 6** (a). Seasonal variations of monthly median wave power, wave power due to swells and wind from 2013/11 to 2014/10 over the area within 30 nautical miles off the coast. (b) Seasonal variations of monthly median significant wave height and mean wave period.

**Figure 7.** Monthly median wave conditions in Aug. 2014 within 30 nautical miles off the coast. (a) Wave power and energy transport direction due to swells; (b) Wave power and energy transport
direction due to local winds; (c) Significant wave height and mean wave direction; (d) Mean wave period. POWER: average wave power over the area; WDIR: average wind direction over the area; WS: average wind speed over the area; HS: average significant wave height over the area; TM01: average mean wave direction over the area.

![Figure 8. Distribution of Annual median wave power along the south coast of Java Island](image)

4. Site Selection
The selection of locations for deployment of wave energy farms or converters is an issue involving wave conditions, technical feasibility, economic benefit and environmental impact. Three simple criteria for preliminary screening of locations suitable for wave energy farms are presented as follows:
1. Annual median power is larger than 20kW/m;
2. Water depth is less than 200m and greater than 30m;
3. Distance to the coast is less than 12 nautical miles.

Based on the described criteria and one-year output from CWM, regions unfit for wave energy farms are filtered. Figure 8 shows suitable locations, which appears mainly off the middle part of the coast, concentrating on two zones, marked by dash lines.

Since the swells is more likely to approach the eastern and middle part of the Java Island at first, annual median power in most areas off the western part of the coast is lower than 20kW/m, insufficient for wave energy farms. On the other hand, water depth off the eastern part of the coast is deep, more than 200m in most areas. Mooring wave energy converters in that location is more difficult and more costly than in shallower water, although the annual median power is acceptable.

5. Summary
Long-term analysis of wave data from ERA-Interim over 10 years at the 18 points along the isobath of 2000m suggests that there is considerable wave energy available off the south coast of Java Island. Detailed wave conditions are revealed from the buoy data and the coastal wave model, CWM. Generally, the majority of wave energy in this area is provided by swells from southwest produced in mid-latitude region. Thus, the swells as well as the wave power due to the swells in the study area strengthen or recede along with the seasonal variation of the westerlies. From 2013/11 to 2014/10, the highest monthly wave power of 31kW/m appears in Aug., 2014. Additionally, from the 2D spectrums of the buoy data and the wave case studies, another wave system due to southeasterly swells is found and dominates the wave field in average wave conditions in the dry season. Although the mild...
southwesterly trade wind of speed about 3-5m/s through the year only have limited local impact on waves, the waves will grow through the fetch and perform as relative weak southeasterly swells when approach the study coastal area. After setting annual median wave power, water depth, and distance from the coast as criteria, two zones suitable for wave energy farms emerged. Zone A has the highest annual median power around 23kW/m. Zone B has more suitable locations where some of them are close to the coast. But for further screen the suitable locations for deployment of wave energy farms, more detailed measurement and associated environmental and economical evaluation are required. In the future, assimilation method can be applied to further improve the model results and help to perform detailed evaluations for specific wave energy converters.

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