Seasonal wave characteristics in Southern Bali Waters in 2014

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Abstract. Seasonal characteristics of wave height in Southern Bali waters (SBW) in 2014 was simulated using SWAN (Simulating Wave Nearshore) model with the resolution of 1/216° (0.51 km). The model was forced using Cross Calibrated Multi Purposed (CCMP) wind data with resolution 1/4° (27.75 km) and 1/600° (0.18 km) bathymetry data derived from Batimeti Nasional (BATNAS) provided by Geospatial Information Agency (BIG). The result shows that the highest (lowest) seasonal average of Significant Wave Height (SWH) in the SBW in 2014 during east (west) monsoon or JJA (DJF) in June-July-August (December-January-February) months was about 2.2 m (1.4 m). Meanwhile, SWH during the first (second) transitional monsoon or MAM (SON) in March-April-March (September-October-November) months was about 1.7 m (2.1 m). The 2D spectrum analysis exhibits that seasonal wave characteristic in the study region was dominated by swell propagation from the Indian Ocean (IO) associated with the Gallian Cyclone. Corresponds to the SWH, seasonal average of wave energy spectrum during east monsoon (JJA) shows the highest value up to 0.0038 m²/deg compared to the other seasons.

Key Words: Wave height, SWAN (Simulating Wave Nearshore), Southern Bali, seasonal characteristics

1. Introduction
The Southern Bali waters (SBW) is located directly exposing to Indian Ocean (IO) and close to exist passages of Indonesian throughflow (ITF) into the IO, especially through Lombok Strait [1]. The Lombok Strait itself has very strong current and has high potential current energy for renewable electricity development [2]. In addition, the estuary region in Benoa Bay (BB) that is a part of the SBW has suffered environmental problems, such as eutrophication and pollution caused by port activities. For this reason, information about hydrodynamics data such as water level and current in the BB is very important to predict and mitigate coastal marine environmental issues which occur in the BB [3]. In addition, large frequent events occurring in the IO, such as tropical and extratropical cyclones, can affect wave characteristics in Indonesian waters including the SBW [4, 5]. During 2000 – 2014, there was an increase in frequency of occurrence of tropical cyclones in the IO [6]. High wave events that often occur in the SBW can result in abrasion along the coast [7]. Moreover, various activities in the marine sector such as sea transportation and trade activities, fisheries, tourism, and marine development are strongly influenced by weather and changes in sea condition [8]. Therefore, the wave characteristics in the SBW are very interesting and important to be studied.
Ocean waves are generally dominated by swell and wind waves [9]. In the Indonesian waters, wave characteristic (e.g., height, period, direction, seas, and swell) and its variation is mostly influenced by northwesterly and southeasterly monsoon winds [10]. Swell in tropical waters, such as in Indonesian waters, was dominated by the presence of swell propagation from high latitude to equatorial region that occurs throughout the year [9]. Therefore, information about wind and wave condition becomes the most important part to reduce losses in all activities in marine sector.

To the best of our knowledge, seasonal wave characteristic in the SBW is still limited, especially in relation to the tropical cyclone events. Gillian cyclone that occurred on 18 – 27 March 2014 has an impact on weather conditions in Indonesia, including in the SBW. The perceived impact of the cyclone is strong winds, heavy rain, and extreme waves [17]. Thus, it is challenged to investigate the wave characteristic in the SBW associated to Gillian cyclone. One way that can be done to obtain information on wind and wave conditions is by forecasting using numerical models [11]. For reasons explained above, we aim to find out the seasonal wave characteristics in the SBW using Simulating Wave Nearshore (SWAN) model [13] in the period of 1 December 2013 – 30 November 2014 in which the Gillian cyclone occurs from 18 to 27 March 2014 as mentioned above. The outline of this paper is introduction in Section 1 and a description of model domain is described in Section 2. Section 3 provides the data and method. Model results and conclusion are given in Section 4 and 5, respectively.

2. Model Domain
This research focuses on the SBW regions with coordinate of 8.5° – 9.5° S and 115° – 116° E. The SBW is located directly facing to the IO and influenced by monsoon winds. Figure 1 illustrates bathymetry profile with depth of about 4000 m in southern part of the study domain and shallowest depth around 10 m in Badung Strait.

![Figure 1. Model domain and bathymetry profile.](image)

3. Data and Method
The current research used a multi-scale nesting approach with four different domains model of D1-D4 (Table 1, Figure 2) to hindcast the wave height in the SBW. The SWAN model was run by using open
boundary data from WAVEWATCH III (WW3) simulation in D1 domain to accommodate swell propagation from high latitude.

In addition to the open boundary data, wind and bathymetry data were also utilized as model input. Wind data at 10 m above sea level was obtained from Cross Calibrated Multi Purposed (CCMP) with a resolution of 1/4° (27.75 km) and with time interval of 6 hours. Bathymetric data of D1-D3 domains was obtained from Global Bathymetric Chart of Oceans (GEBCO 30°), whereas 1/600° (0.18 km) bathymetric data of D4 was derived from Batimetri Nasional (BATNAS) provided by Geospatial Information Agency of Indonesia (BIG). Open boundary input for D2 was obtained from the WW3 hindcast wave in the Indonesian waters (D1 domain: 20° N – 20° S dan 90° – 150° E) with a resolution of 1/8° (13.87 km). Simulations were carried out by ignoring the effect of tides and changes in depth due to sediment transport. Hence, the depth value was considered constant during the simulation period.

Table 1. Multi-scale nesting model domains.

| Name of Domains | Coordinates              | Grid Sizes  |
|-----------------|--------------------------|-------------|
|                 |                          | (°)         | (km)        |
| Domain 1 (D1)   | 20° N – 20° S and 90° – 150° E | 1/8 x 1/8   | 13.875      |
| Domain 2 (D2)   | 3° – 17°S and 100° – 130° E | 1/24 x 1/24 | 4.625       |
| Domain 3 (D3)   | 6° – 11°S and 112° – 116.5° E | 1/72 x 1/72 | 1.540       |
| Domain 4 (D4)   | 8.5° – 9.5°S and 115° – 116° E | 1/216 x 1/216 | 0.524      |

Figure 2. Multi-scale nested method used in the study (D1 is WW3 domain and D2, D3, D4 are SWAN nested domains).
SWAN is a near-shore third-generation wave model developed at Delft University of Technology, Netherlands [12, 13]. The wave parameters generated by wind in the coastal area, lake, and estuaries can be estimated using the SWAN model [13]. The model is based on the wave action balance equation, as follow [14]:

\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} C_{g,x} N + \frac{\partial}{\partial y} C_{g,y} N + \frac{\partial}{\partial \theta} C_{g,\theta} N + \frac{\partial}{\partial \sigma} C_{g,\sigma} N = \frac{S_{tot}}{\sigma} = \frac{S_{in} + S_{nl} + S_{ds} + S_{bot}}{\sigma}
\]  

(1)

where \(N(\sigma, \theta)\) is the action density spectrum expressed by \(N = \frac{E}{\sigma}\) in which \(E(\sigma, \theta)\) is the energy density spectrum and \(\sigma\) is relative frequency, \(t\) is time, \(\theta\) is wave direction, \(C_{g,x}\) and \(C_{g,y}\) are the propagation velocities in \(x\) and \(y\)-direction, respectively. Moreover, the terms at the right-hand side of the Equation (1) are the source and sink terms of energy density, that represent generation by wind (\(S_{in}\)), dissipation process (\(S_{ds}, S_{bot}\)), and non-linear wave-wave interaction (\(S_{nl}\)) [12, 16].

4. Model Results
Verification of the simulated wave height with the observation data has been carried out in the previous study (see Figure 3 in [15]). The verification result shows good agreement between the simulated and observed significant wave height with coefficient correlation (CC) 0.59, Root Mean Square Error (RMSE) 0.44 m, and Bias -0.17 m (see Table 1 in [15]).

4.1 Seasonal Wind and Significant Wave Height Characteristics
In general, the model results show that simulated significant wave height (SWH) is associated with the existing wind fields, especially in its direction, in the study area during west monsoon or DJF (December-January-February) as illustrated in Figure 3. However, the simulated SWH is not associated with the local wind during first transitional monsoon or MAM (March-April-May), east monsoon or JJA (June-July-August), and second transition monsoon or SON (September-October-November) as shown in Figures 4, 5, and 6, respectively. In this case, we suggest that swell propagation from high latitude dominates wave fields in the SBW [9].

Figure 3. Average wind field (a) and significant wave height (b) for DJF in 2014. Arrows show wind and SWH direction.
Figure 3 presents a spatial plot of wind and SWH in the SBW during DJF in 2014. The wind blows from southwest with magnitude of 1.6 m/s and wave propagates toward northeast with SWH of 1.4 m, which is the lowest wave height compared to other seasons.

![Figure 3](image)

**Figure 4.** Same as in Figure 3 but for MAM in 2014.

During MAM (Figure 4), the wind blows from southwest with magnitude of 0.9 m/s which is the lowest magnitude compared to other seasons. In this season, wave propagates toward northeast with a SWH of about 1.8 m. The SWH average during MAM is greater than that during DJF even though the wind speed during MAM is weaker compared to that in the period of DJF. It is suggested that there is a dominance of swell propagating from high latitude in the IO over wind-sea regimes during the MAM.

![Figure 4](image)

**Figure 5.** Same as in Figure 3 but for JJA in 2014.
Similar to MAM season, SWH during JJA and SON are not also associated with the local wind. During JJA (Figure 5), the wind blows from southeast with magnitude of 4.5 m/s. Meanwhile, wave propagates toward north with a SWH of 2.2 m. This result shows that wind (SWH) is strongest (highest) during the JJA compared to other seasons. Moreover, during SON, the wind blows from southeast with a magnitude of 3.9 m/s, whereas wave propagates toward northeast with a SWH of about 2.1 m (Figure 6). We also suggest that swell dominates over wind seas in the study area during JJA and SON and this characteristic is consistent with research conducted by [9].

![Figure 6](image.jpg)

**Figure 6.** Same as in Figure 3 but for SON in 2014.

### 4.2 Directional Wave Spectra

Based on the wave energy spectrum, characteristics of seas and swell in waters can be studied by analyzing dominant wave energy and direction as well as local wind direction [10]. Three observation points were chosen to study characteristics of wind seas and swell in the SBW (Figure 7). Point 1 (marked by P1 in Figure 7) represents deep seas, whereas Point 2 (P2) located in the Lombok Strait and Point 3 (P3) situated in Badung Strait represent the shallow water area.

![Figure 7](image.jpg)

**Figure 7.** Three observation points in the SBW.
Seasonal average of wave energy spectra at P1, P2, and P3 are shown in Figures 8, 9, and 10, respectively. In general, swell propagating northeastward is found in every season at the three observation points, which it is characterized by peak energy density with small frequency (< 0.1 Hz), as shown in Figures 8-10. Meanwhile, there is a dominance of wind seas (waves generated by local wind) over swell during DJF which it is characterized by the existence of peak energy density in northeast direction associated with strong southwesterly local wind (2.2 – 2.3 m/s). Meanwhile, during MAM, although the local southwesterly wind is weaker (1.1 – 1.2 m/s) than that during DJF (2.2 – 2.3 m/s), waves with the energy density (0.00019 - 0.0025 m²s/deg) during MAM are the highest than that during DJF (0.00014 - 0.0013 m²s/deg, as shown in Table 2). Therefore, we suggest that although the waves are almost in the same direction with the southwesterly local wind during MAM, swell dominates over wind seas at points P1, P2, and P3 area during this season.

![Figure 8](image)  
**Figure 8.** Seasonal average of wave spectrum a) DJF, b) MAM, c) JJA and d) SON at P1.
Table 2. Seasonal average of wave energy density at P1, P2, and P3

| Seasons | Wave Energy Density (m²/s/deg) | Magnitude Wind Speed (m/s) |
|---------|--------------------------------|---------------------------|
|         | P1    | P2    | P3    | P1    | P2    | P3    |
| DJF     | 0.0013| 0.0012| 0.00014| 2.3   | 2.2   | 2.2   |
| MAM     | 0.0025| 0.0020| 0.00019| 1.1   | 1.2   | 1.2   |
| JJA     | 0.0038| 0.0032| 0.00030| 6.2   | 5.5   | 5.5   |
| SON     | 0.0032| 0.0030| 0.00031| 5.3   | 4.8   | 5.0   |

Table 3. Seasonal average of peak wave energy density at P1, P2, and P3

| Seasons | Peak Wave Energy Density (m²/s/deg) | Magnitude Wind Speed (m/s) |
|---------|-----------------------------------|---------------------------|
|         | P1    | P2    | P3    | P1    | P2    | P3    |
| DJF     | 0.0821| 0.0802| 0.0090| 2.3   | 2.2   | 2.2   |
| MAM     | 0.1571| 0.1552| 0.0117| 1.1   | 1.2   | 1.2   |
| JJA     | 0.2219| 0.2187| 0.0195| 6.2   | 5.5   | 5.5   |
| SON     | 0.2226| 0.2188| 0.0190| 5.3   | 4.8   | 5.0   |

The average energy density at P1 (P2) during JJA (Figure 8.c (9.c), Table 2) shows the highest value compared to other seasons up to 0.0038 m²/s/deg (0.0032 m²/s/deg) and exhibits the lowest value during DJF (Figure 8a, 9a, Table2) up to 0.0013 m²/s/deg (0.0012 m²/s/deg). The highest energy density during JJA is due to domination of swell and also caused by wind seas due to local wind speeds which are stronger compared the other seasons. However, at P3 (Figure 10.d, Table 2), the highest energy density occurs up to 0.00031 m²/s/deg during SON and the lowest energy density experiences during DJF up to 0.00014 m²/s/deg (Figure 10a, Table 2). The maximum peak wave energy density value at P1 (P2) up to of 0.2226 m²/s/deg (0.2188 m²/s/deg) is found during SON and the minimum peak wave energy is captured during DJF up to 0.0821 m²/s/deg (0.0802 m²/s/deg) (Table 3). However, the maximum peak wave energy density value at P3 influenced by wind waves up to 0.0195 m²/s/deg is found during JJA and the minimum peak wave energy is discovered during DJF up to 0.0090 m²/s/deg (Table 3). In general, waves caused by swell at P1 and P2, which are located in the offshore area, have higher wave energy density compared with at P3. The minimum wave energy at P3 is supposed due to its location behind island and influenced by wind seas (Figure 7).
Figure 9. Same as in Figure 8 but at P2.
Figure 10. Same as in Figure 8 but at P3.

5. Conclusions
In general, SWH during DJF is associated with local wind. However, it is not associated during MAM, JJA, and SON, respectively. The highest seasonal average of SWH in SBW in 2014 during JJA is about 2.2 m and the lowest during DJF is about 1.4 m. Meanwhile, SWH during the first transitional monsoon (MAM) and second transitional monsoon (SON) is about 1.7 m and 2.1 m, respectively. The 2D spectrum analysis exhibits that seasonal wave characteristic in SBW are dominated by swell propagation from the IO associated to the tropical Gillian cyclone occurred in SBW 2014. Meanwhile, there is a dominance of wind seas (waves generated by local wind) over swell during DJF. The seasonal average wave energy spectrum at P1 during JJA (DJF) shows the highest (lowest) value of 0.0038 m²/s/deg (0.0013 m²/s/deg). At P2 the highest (lowest) energy density occurs during JJA (DJF) of 0.0032 m²/s/deg (0.0012 m²/s/deg). Whereas, at P3, the highest (lowest) energy density occurs during SON (DJF) of 0.00031 m²/s/deg (0.00014 m²/s/deg). Energy density at every point is associated with the wind and SWH during each season. Moreover, importance of depth and location of observation points contributes to the energy density.
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