Influence of variability to coastline dynamic in the small uninhabited reef islands of Kepulauan Seribu

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Abstract. Small reef islands provide habitable land for coastal communities in many parts of the world. However, the small, low lying reef islands are commonly considered among the most geomorphically sensitive landforms to changes in sea level, wave processes, sediment supply and anthropogenic impacts. Kepulauan Seribu in the Java Sea comprise of numerous reef islands. By 2019, the islands chain is host to more than 24 thousand people. Kepulauan Seribu is affected by monsoon wind cycle. The monsoon wind also known to interact with an interannual phenomenon such as Indian Ocean Dipole (IOD) which affecting regional and local wind circulation. This study aims to examine the reef shoreline response to seasonal and interannual climate variability using satellite data that encompasses yearly monsoon cycle and IOD event. Strengthens (weakens) of winds speed in the study area during the East (West) Monsoon, which in some year also coincides with a positive (negative) IOD event, are observed from 2009 to 2018 ERA - Interim by The European Centre for Medium - Range Weather Forecasts (ECMWF) data. This variability influences the shoreline shifting in the uninhabited reef islands of Kepulauan Seribu as identified based on satellite imagery analysis. More pronounce shifted of large sediment flux are perceptible on opposing monsoon which coincides with positive/negative IOD event. Small uninhabited reef islands have ecological and economical value. Hence, enhancing coastal resilience from erosion by using conservation-types approach should be taking into consideration. Ultimately, a good understanding of climate variability that controlled changes in beach systems of reef islands is important for adequate coastal management decisions.

1. Introduction

Indonesian archipelago comprises more than 17.000 islands. Large islands, including Sumatra, Java, Kalimantan, Sulawesi and Papua are inhabited by the majority of Indonesia’s population. There are thousands of smaller reef islands located within the adjacent tropical seas of Indonesia which known as the world’s most diverse and abundant coral reef systems. These smaller islands usually provide habitable land for coastal communities.

Reef islands throughout the Indonesian archipelago are usually low lying coasts, rarely being more than 2 - 3 m above sea level, composed of carbonate sediments from break down of corals, mollusc, coralline algae, and other carbonate secreting organism from adjacent coral reef environments [1,2]. Low elevation, small reef islands are widely considered among the most geomorphically sensitive landforms to changes in sea level, wave processes, sediment supply and anthropogenic impacts [3,4]. From changes in island stability and flooding to extreme scenario of
submerged island, these are the real threat and serious consequences for island communities that need to be address.

Major process mechanism that controls the formation and stability of reef islands is known to be wave action and its interaction with coral reef platform [3]. One of the implications of wave-reef interaction is that the changes in direction of incident wave energy are likely to shift the nodal point of deposition and promote island and shoreline change [4]. Fluctuations in island building processes over short term seasonal changes in wind, waves and currents can result in significant changes in island shape, size and position of reef, thus making them inherently dynamic landform [4].

Among the best-known coral reef islands in Indonesia is Kepulauan Seribu, located about 10 km north of Jakarta Bay extends for about 50 km north into the Java Sea. By 2019, the reef islands are host to more than 24 thousand people. Kepulauan Seribu is facing threats from urban pressure and pollutant [5,6] as well as erosion due to natural event such as wind and wind generated waves [7,8]. Kepulauan Seribu area is affected by monsoon wind cycle. Movement of beach sands driven by the alternating monsoonal wind-induced waves in Kepulauan Seribu occasionally results in negative sediment budget [9]. Moreover, the monsoon wind is known to interact with an interannual phenomenon such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) which affecting regional and local wind circulation patterns in Indonesia waters [10]. A positive (negative) IOD strengthens (weaks) the winds speed in Java Sea during the East (West) Monsoon and hence contributes to increasing (decreasing) the significant wave in Java Sea [11].

Basic understanding of many physical processes including erosion on small islands can be initiated by observing the displacement or changes of position of any related features with respect to its spatial setting [7]. Predictable shifts in monsoon wind directions on a seasonal timescale affect the short-term geomorphology of reef islands as wind waves are able to entrain reefal and beach sediments and transport it to depositional nodes around the island footprint [3,4]. Specific objective of this study is to examine the reef shoreline response to seasonal climate variations using satellite data that encompasses yearly monsoon cycle and positive/negative IOD event. Ultimately, Kepulauan Seribu provides a natural laboratory to evaluate the effect of changing climate on coral island shoreline change. A good understanding of monsoonal controlled changes in beach systems of reef islands is important for adequate coastal management decisions.

2. Study area

Kepulauan Seribu (The Thousand Islands) is situated in the Java Sea, north of Jakarta Bay (figure 1). It consists of numerous coral reef islands ranging in size from a few meters across to length greater than one kilometer. The patch reef system of Kepulauan Seribu is located on the shallow Sunda Shelf where it rises from a water depth of 30 to 50 m to the sea surface. Each island and platform of Kepulauan Seribu is built up from the skeletal debris of coral reefs which rim the platform margins [12,13]. The steep reef front extends seaward from the reef crest to a depth of about 15 meters. Well-developed reef facies occur down to a depth of about 16 - 18 m [13]. Reef framework builders at Kepulauan Seribu consist of a diverse fauna of Indo-Pacific corals and encrusting red algae. The dominant bioclasts are coral and mollusc fragments, with benthic foraminifers, red algae, green algae, and echinoderms in lesser amount [1]. The sedimentation on the lagoon and deeper water below the wave base further away from the direct influence of the reef system is influence by siliciclastic mineral [14].
Figure 1. Kepulauan Seribu islands chain in the Java Sea. Shoreline changes were examined in Semak Daun and Opak Kecil reef platforms as indicated in the red squares area.

Kepulauan Seribu is facing threats from anthropogenic pressure and natural event. Urban pressures and pollutants from rivers entering Jakarta Bay have been reported to cause environmental degradation of ecological conditions in Kepulauan Seribu [5]. Due to their close proximity to Jakarta Greater Area, unregimented tourism, and non-sustainable fishing activity, Kepulauan Seribu also at risk of polluted water mass and microplastic contamination [6]. Environmental issue such as saline water intrusion and erosion on local scale are also reported in Kepulauan Seribu [7]. Saline water intrusion increases the risk of freshwater availability, while erosion may destruct beach line belt and caused reduction of island total size [7].

The controlling influence on modern reef growth and morphology in Kepulauan Seribu is believed to be the seasonal change in the wind and current directions which are controlled by the monsoonal climate [12]. The Java Sea is characterized by the monsoonal wind with a seasonal reversal between the West Monsoon (December to February) and East Monsoon (April to October). The seasonal East Monsoon phase lasts longer but is characterized by lower maximum wind speeds compared to the West Monsoon. On the interannual timescale of more than five to seven years this relationship reverses with higher wind magnitudes during the East Monsoon [8]. The longer-lasting winds of the East Monsoon (eight months) are thought to be more important for beach erosion, despite the somewhat lower wind magnitudes on seasonal timescales [8]. The Java Sea also identified to capture IOD effect. Simulated model using data from July 1996 to 1999 acknowledge that in July to September, winds in the Java Sea move westward and reinforced by a positive IOD which drive stronger winds westward around Java Sea [11]. In December to February, movement of winds eastward in Java Sea is reduces by positive IOD [11].

The focus of this study are the small, uninhabited reef islands of Semak Daun (-5.73°S, 106.57°E) and Opak Kecil (-5.68°S, 106.58°E), located in the middle range of Kepulauan Seribu island chain (figure 1). Most of the big islands in Kepulauan Seribu are inhabited, many are intensely
developed and underwent shoreline structures to disrupt natural shoreline processes. The uninhabited reef islands, on the other hand, are mostly undisturbed or subject to minor build infrastructure. They mostly served for conservation or tourism.

3. Methods
Climatology of monthly average wind from 2009 to 2018 in Kepulauan Seribu water and its surrounding were obtained from ERA-Interim (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). The analysis was done using MATLAB 2017. Wind data show the vector represented by the direction and wind speed (m/s). The mean of wind data of each according month was calculated. The spatial of wind data were plotted using MATLAB following the script by Pawlowicz (2020) [15].

Indian Ocean Dipole (IOD) climate variability index data used Dipole Mode Index (DMI) provided by https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php. DMI is a value derived from differences in sea surface temperature anomalies in the West Indian Ocean (10°N - 10°S and 50°E - 70°E) and East Indian Ocean (10°S - 0°U and 90°E - 110°E) [16], based on the period of 2009 to 2018. Moving average was done to change the data from weekly to 3 monthly averages. The data were plot following the script from Green (2021) [17] using anomaly plot.

Physical changes examination of coral islands in the study area were considered based on satellite imagery analysis in the Google Earth. The timeframe analysis was based on the availability of the satellite imagery. Shoreline changes were examined due to its susceptibility to high frequency change promoted by variations in tidal and wave conditions. Once the shoreline was determined for each time interval, its length and area were calculated.

4. Result and discussion
Climatology of monthly average wind from 2009 to 2018 in the Kepulauan Seribu water is shown in figure 2. The directions of wind magnitude in Kepulauan Seribu water show bimodal distribution pattern that changes direction almost 180° in one year, ranging from 90° to 150° for West Monsoon and 310° to 325° for East Monsoon (figure 2). During West Monsoon from December to February the maximum monthly average wind occurs and weaken in April. The wind strengthens again in May to October which is known as the East Monsoon and weaken again in November. The West Monsoon wind are known to be stronger than the East Monsoon wind, but less persistent. It is thought that the persistence mechanism from East Monsoon winds dominates the process of sediment transport and considered to overwhelm the higher wind magnitudes during West Monsoon [8].

The Dipole Mode Index (figure 3) measures the strength of the Indian Ocean Dipole, with positive values indicating the positive phase and negative values indicating negative phase. Positive IOD phase typically peak in September - October and dissipate by November. Negative IOD phase usually developed from late August to late November. When the Dipole Mode Index is near zero such as in 2008 and 2009, it indicates that the IOD is in neutral condition (figure 3).
Figure 2. Climatology of monthly average wind from 2009 to 2018 in the Kepulauan Seribu water and its surrounding. Vector orientation indicates the direction of the resultant wind, and the colour bar indicates the wind speed (in m/s).

Figure 3. (A). Dipole Mode Index (DMI) from 2009 to 2018. Blue (red) field indicate negative (positive) Dipole Mode event as classified according to the Australian Government Bureau of Meteorology in http://www.bom.gov.au (data source: https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php).

Major mechanism that controls formation and stability of reef island is interaction of wave with coral reef platform, which imply that i.e., changes in direction of incident wave energy are likely to
shift nodal point of depositional and promote shoreline change [3,4]. Poerbandono was the first to examine shifting of shoreline position in Kepulauan Seribu, focusing on Pramuka, Panggang, Karya and Semak Daun islands [7]. Visual interpretation of Quickbird image in July 2008 (SE Monsoon) and WorldView image in December 2009 (NW Monsoon) indicates that there is considerable visible change of shoreline position [7]. In this study, shoreline shifting due to opposing monsoon in Semak Daun also observed as indicated by satellite images (figure 4). Shoreline position is shifted south-eastward during West Monsoon and north-westward during East Monsoon. In December 2009 (West Monsoon), satellite imagery observation imply that shoreline was tied in with vegetated boundary (figure 4). Average monthly windspeed show that the wind during this time was weak and Dipole Mode Index indicating a neutral mode (figure 3). In July 2011 (East Monsoon), the shoreline was shifted north-westward and was visible in the western tip of the island (figure 4). The shifted shoreline positions were frequently observed on opposing monsoon which coincides with positive/negative IOD event (figure 4). More pronounced north-westerly shift of sediment flux was observed during the East Monsoon in September 2015 (figure 4) which coincided with a positive IOD event (figure 3). Whereas narrower reef flat was observed on the western tip of the island as the shoreline shifted south-eastward during November 2014 (figure 4). This period represents a transition from East to West Monsoon that also coincides with negative IOD event (figure 3).

Likewise, the shoreline shift also occurred at Opak Kecil (figure 5). The Shoreline was shifted south-eastward during West Monsoon and seemed to tie in with water-vegetated boundary on the island. Shoreline position tends to move to north-westward during East Monsoon along with development of sand spit on the western reef flat (figure 5). Shoreline shift due to opposing monsoon were observed throughout all the years, however positive/negative IOD event seems to give more effect on the shoreline movement compare to neutral IOD years (table 1). Major process mechanism that controls the formation and stability of reef islands is known to be wave action and its interaction with coral reef platform [3]. Rachmayani (2018) [11] pointed out that a positive (negative) IOD
strengthens (weakens) the wind speed in Java Sea during the east (west) season and hence contributes to the increasing (decreasing) significant wave in Java Sea. Apparent evident of strengthening monsoon winds on interannual scale due to influence of IOD is observed in Semak Daun and Opak Kecil reef platforms (figure 4 and figure 5). For most of the uninhabited islands in Kepulauan Seribu, major changes in the shoreline positions that coincides with IOD positive/negative event is recognizable especially if the width of reef flat is sufficient for unconsolidated beach sediment to move. When the reef flat is narrow or the island is having close seaward boundary to reef slope, the shoreline will undergo only minor changes due to limited area for shoreline to move freely.

Figure 5. (A). Shoreline shifting in Opak Kecil reef platform due to opposing monsoon. Colour lines represent shoreline during different monsoon cycle and IOD event. Green: East Monsoon, September 2008. Yellow: West Monsoon, December 2009. Blue: (transition to) West Monsoon, November 2014. Red: East Monsoon, September 2015. Images from Google Earth (Dec 2009). (B). Opak Kecil location in Kepulauan Seribu as indicated in the red square.

Table 1. Length of shoreline on the observed reef platforms. *Source: http://www.bom.gov.au.

| Reef platform | Image date | Monsoon        | IOD year  | Shoreline length (m) | Area (m²) |
|---------------|------------|----------------|-----------|----------------------|-----------|
| Semak Daun    | Dec-09     | West           | neutral   | 455                  | 9,715     |
|               | Jul-11     | East           | weak positive | 500           | 11,522    |
|               | Nov-14     | transition to West | negative* | 520                  | 10,197    |
|               | Sep-15     | East           | positive* | 560                  | 11,631    |
| Opak Kecil    | Sep-08     | East           | weak positive | 665           | 19,082    |
|               | Dec-09     | West           | neutral   | 640                  | 17,772    |
|               | Nov-14     | transition to West | negative* | 614                  | 17,530    |
|               | Sep-15     | East           | positive* | 628                  | 19,344    |
The accretion history of the Seribu carbonates platform is interpreted to initiate during the period of 10,000 – 4,500 years BP when the vertical accumulation was largely achieved [18]. Since 4,500 years BP, the sea levels have been largely stable enabling prograded coral reef growth and buildups [18]. A slight fall in sea level from a highest Holocene level was reconfirmed by the coral dating in the northern island of Kepulauan Seribu, dated at around 4,440 years BP [18]. The reef platforms were exposed to weathering, which promote production of biogenic sediment originated from dead corals. Biogenic sands and gravels were then transported from the reef crest onto the reef flat by waves and currents. Refraction and diffraction of waves promoted on the reef flat. Wave propagation supported by wind generated currents, tide and wave pumping control the entrainment and transport of sediments to areas of least current velocity (i.e. nodal point) where sediment load is deposited [19]. Many of coral islands experienced stabilization once they reached considerable size [20]. However, the instabilized accumulated sandy shoal on reef platform may be a subject to movement due to surfing wind generated wave. Movement of beach sand driven by alternating monsoon induced-waves may occasionally results in negative sediment budget [7,21]. Moreover, the monsoon wind is known to interact with an interannual phenomenon such as IOD which affecting wind circulation patterns in Java Sea [10] which subsequently contributes to increasing/decreasing the significant wave [11].

4.1. Perspective for coastal protection in uninhibited island
The natural dynamics occurred in the islands in response to the monsoon as seen from the aerial images (figure 4 and figure 5). This caused the coastline changes overtime, coastal erosion in some areas and deposition in others. In inhabited islands, erosion and accretion are a great concern since it affects the livelihoods of coastal communities. Meanwhile, in uninhibited island where there is no permanent resident, this phenomenon is mostly overlooked. This is a blind spot in coastal management since uninhabited islands have potential contribution for environment and economy. Several uninhabited islands in Kepulauan Seribu are used for conservation, mostly for Hawksbill turtle (Eretmochelys imbricata) protection and coral reef ecosystem. Several other islands are popular tourist destination suitable for snorkelling and diving activities.

The uninhibited islands in Kepulauan Seribu are a small closed system which are vulnerable to extreme weather events. Reef island stability particularly in tropical regions requires maintenance of healthy coastal ecosystems, degradation of protective reefs will increase exposure to erosion [22]. Coastal protection in form of hard and soft approach has been done in some of inhabited island in Kepulauan Seribu such as Panggang, Tidung, and Pari. Hard structures such as seawall and revetments and soft protection such as mangroves were often built along the shoreline. Although failure of coastal protection and eroded sites were also evidence such as in Pramuka and Semak Daun as they are subjects to monsoon induced-wave [7].

In the small uninhabited island, coastal protection by nature approach is more suitable. First, nature protection can be more resilient and adaptable than hard infrastructure. In some cases, nature protection performs better than hard infrastructure especially for areas that are exposed to high-frequency, low-intensity hazards [23]. Second, nature protection requires lower cost compared to hard infrastructure since natural ecosystems will grow stronger over time while hard infrastructure often deteriorates over a finite lifespan [24]. In order to maintain its sustainability, utilization and management of uninhabited islands should be done with conservation-types approach. Preserving existing habitat is often much less expensive than restoring lost or degraded habitat.

5. Conclusion
Shoreline shifting due to opposing monsoon in uninhabited reef platform of Kepulauan Seribu can be acknowledged from satellite images visual interpretation. In this study area, shoreline position is shifted south-eastward during West Monsoon and north-westward during East Monsoon. Shoreline shifting due to opposing monsoon were observed throughout all the years, however positive/negative IOD event seems to give more effect on the shoreline movement compare to neutral IOD years. For most of the uninhabited islands in Kepulauan Seribu, major changes in shoreline positions that
coincides with IOD positive/negative event is recognized especially if the width of reef flat is sufficient for unconsolidated beach sediment to move. When the reef flat is narrow or the island is having close seaward boundary to the reef slope, the shoreline will undergo only minor changes due to limited area for shoreline to move freely.

Coastal protection in the small uninhabited island is mostly overlooked although they have potential contributions to the environment and economy. In order to maintain its sustainability, utilization and management of uninhabited islands might best be done with conservation-types approach. A good understanding of climate variability that controlled changes in beach systems of reef islands is important for adequate coastal management decisions.

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