

Marine Debris Pathway Across Indonesian Boundary Seas

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ABSTRACT

The complex circulation for both atmospheric and ocean affects the pathways of floating marine debris (MD). The aim of this research was to define the MD trajectories in the Indonesian boundary seas. The Lagrangian particle method was applied with oceanographic factors and debris classes based on 1 to 3% windage class. The simulation was applied during the Northwest and Southeast Monsoon period. On the basis of the obtained findings, the debris trajectory patterns were indicated to vary in the two monsoons. In the northern part of Indonesia, all neighbouring countries were affected, especially those near the boundaries. In the southern part of Indonesia, most of the debris headed west towards the Indian Ocean. MD was mostly transported by the ocean currents and monsoonal wind and ended up in the coastal area. Some debris was also still floating in the open ocean after three months. This study concluded that marine litter not only polluted Indonesia water, but also the neighbouring countries.

Keywords: floating debris; Indonesia Throughflow; marine pollution; wind; ocean currents

INTRODUCTION

Nowadays, marine debris (MD) is one of the most alarming global environmental issues due to its high impact to the ecosystem, human health, and the economy (Beaumont et al., 2019; Purba et al., 2019). Most of MD is made of plastic, wood, metal containers, and fishing gear (nets, lines, buoys, etc.) (Purba et al., 2017), which are materials that can be expected to remain afloat at the surface for an extended period or sink to the bottom. MD includes any floating objects, ranging in size from macro to micro-debris. Furthermore, these kinds of MD mostly ended up in the coastal regions which provide habitat for mangrove, seagrass, and coral reef, and affected them in a long period. MD will reduce the benefits of

ecosystem services and cause economic loss. Every ton of marine plastic reduces the marine natural resources annually by around \$3300 to \$33,000 (Beaumont et al., 2019). Poor cleanliness of the beach significantly decreases the tourism revenue (Krelling et al., 2017; Jang et al., 2014; Williams et al., 2016).

Unmanaged trash from terrestrial ecosystems is one of the main problems due to lack of technology. Jambeck et al. (2015) have published a comprehensive finding of countries weaknesses in managing the trash from terrestrial ecosystems, which includes Indonesia as the second-largest waste producer in the world. However, Purba et al. (2019) stated that Indonesia Seas received trash from two sources. First, from the activities of terrestrial origin, which delivered trash to the

rivers, and second –from other countries, especially those close to Indonesia Seas.

Consequently, MD becomes the leading trans-boundary issue that poses complex challenges globally. The litter in sea regions can move freely in all directions, since it flows with the ocean currents. Ocean circulation in Indonesia Seas flows through most of the Eastern and Southeast Asian countries called the Indonesian Throughflow (ITF) (Gordon et al., 2012; Fieux et al., 1996). From Indonesia Seas, the water also flows to the Indian Ocean. This flow is known as part of global thermohaline circulation (OCB)(Broecker, 1991).

Since 2015, after Jambeck et al. (2015) published their paper, the studies about marine debris in Indonesia have increased exponentially (Purba et al., 2019a). Previous studies have shown that MD is found in the coastal areas (Maharani et al., 2018; Purba et al., 2019b), ecosystems and up to the open sea (Hiwari et al., 2019; Lebreton et al., 2018), and deep-sea (Cordova and Wahyudi, 2017). Most of those studies focus on weight, distribution, and type of debris. Furthermore, unusual trans-oceanic journeys involving human-made debris objects were documented, often with better details about the source, destinations, and time of travel (Pearce et al., 2019). In order to identify the pathways of debris in the ocean, several researchers have used various methods. Several scientists compared models and observation data (Onink et al., 2019; Seville et al., 2020), modeled the global distribution of microplastic based on drogue surface drifter trajectories (Maximenko et al., 2012) or modeled surface currents (Lebreton et al., 2012), and predict the source of debris by using a hypothetical method (Handyman et al., 2018).

This paper was aimed at representing the marine debris trajectories in Indonesia Seas boundaries and emphasizing the patterns. This study is a step forward towards a comprehensive understanding of the marine debris behavior in the complex waters of Indonesia. The output of this research will support policies at both the national and regional levels in Southeast Asia (SEA). Simulated MD trajectories are very challenging due to complex oceanographic factors. On the basis of the previous literature work, this type of research has not been done much, as Indonesian waters have a very complex circulation (Purba et al., 2019a). The Indonesian Seas influenced by monsoons that affect surface circulation, bathymetry to deflect ocean currents, ITF, eddies, and local conditions (Gordon et al., 2012; Khan

et al., 2020). In order to obtain a better explanation about the spreading of MD in Indonesia Seas, the research that covers the combination of these features is needed.

GNOME (General NOAA Operational Modeling Environment) developed and used by the NOAA (National Oceanographic and Atmospheric Administration) was employed in research. The previous study of debris transport modeling using GNOME has shown that it is capable of modeling the marine debris trajectory (Maximenko et al., 2018; Duran et al., 2018). Therefore, this free software was utilized to simulate the debris trajectory in Indonesian boundary seas. GNOME is the latest spill-trajectory model developed by the Hazardous Materials Response Division (Beegle-Krause, 2005). Several scientists have recommended this software (Hardesty et al., 2017) and used it to identify the debris trajectories (Zelenke et al., 2012). Maximenko et al. (2018) have used this software to analyze the debris transport from the evidence of Japan Tsunami 2011. The concept is that the drift of any floating object (including debris) on the ocean surface is influenced by currents, waves and wind (Duhec et al., 2015; Durgadoo et al., 2019). Therefore, the trajectories of debris as floating objects can be analyzed using these influences as factors.

MATERIALS AND METHODS

Geographic Locations

For this study, the transects based on the main pathway of ocean currents in Indonesia Seas were proposed (Gordon et al., 2012). Five transects on the northern side to represent the boundary areas with neighbouring countries (SEA Countries) and the Pacific Ocean (Fig 1: A-E). The distance of the starting point at each transect varies from 50–200 meters depending on the width of the waters. Transect A is the Malacca Strait that has a boundary with Malaysia whereas Transect B borders Malaysia, Singapore and Brunei Darussalam. Transect C, D and E are bordered by Malaysia, Philippines and the Pacific Ocean. Then, four transects in the southern side trajectories represent boundary areas with Australia (F), Timor Leste (G), and the Indian Ocean (Fig. 1: F-I). These transects are the areas where the debris transported by the ITF and other circulation passes through the straits.

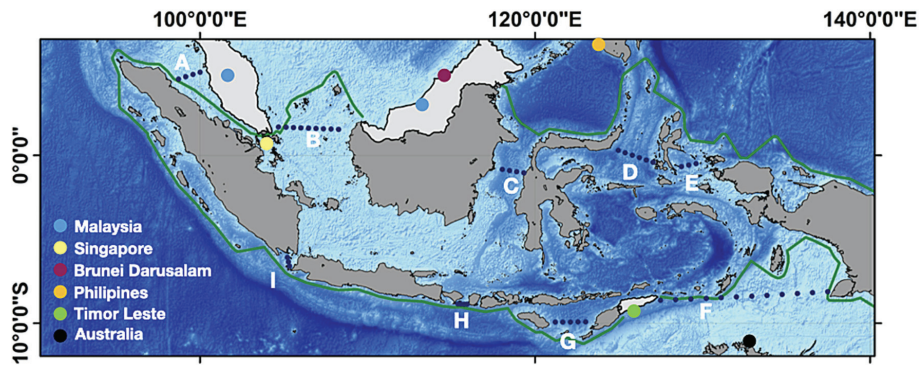


Figure 1. Indonesian Seas overlaid with bathymetry and neighbouring countries. Dash line represents the starting point of marine debris and sea boundaries, A) Malacca Strait, B) Natuna Sea, C) Makassar Strait, D) Maluku Sea, E) Halmahahera Sea, F) Aru Sea, G) Savu Sea, H) Lombok Strait, I) Sunda Strait

The northern waters include shallow waters (fig1: A, B) and deep waters (fig1: C, D, E), and the outflow areas are characterized by deep waters. The paths of the large-scale circulation from the Pacific Ocean to Indonesia cross the transect C, D, and E and pass through the transect B (Fieux et al., 1996). Furthermore, the water flows from Indonesia is dominant through transect H, G, and F and the rest pass through transect I. The prevailing winds in these areas are the seasonally-shifting monsoon winds. The easterly wind blows from Australia with a correspondingly low rainfall rate and the westerly wind blows from the Asian continent with much-enhanced convection and rainfall (Wheeler and McBride, 2005). The tidal phenomena in the Indonesian seas are among the most complex in the world, with complicated coastal geometries, narrow straits, small islands, and large quantities of input from the adjacent Indian and the Pacific Ocean. Semidiurnal tides are particularly strong in I, H, G, and F in response to the tidal force from the Indian Ocean (Ray et al., 2005). The seas chosen for this study are linked to the global sea-stream via the Indonesian Throughflow (ITF). These areas are the main pathways for the ITF (Sprintall et al., 2014). Therefore, it is crucial to understand how debris behaves in these pathways since these are the only tropical pathway in the thermohaline circulation.

Data

The GNOME model approach includes particles with a range of windage values to represent diverse debris types and behaviors, including high windage objects, with values derived from experimental data in the USCG windage/leeway library (please see: <https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome-suite-oil-spill-modeling.html>). GNOME requires specific map which includes bathymetry and boundary conditions, ocean currents, wind and windage range (Table 1).

The windage range is a percentage of the wind that moves the debris. Therefore, it is dependent on whether it floats on the surface or submerged (Caitlin O'Connor: personal communication). During this process, GNOME version 1.3.10 was used. The wind and current data were then averaged for five days to obtain a seasonal pattern. A seasonal depiction is required because the territorial waters of Indonesia are affected by monsoons that move periodically, i.e. Northwest Monsoon (NWM) and Southeast Monsoon (SEM) (Utamy et al., 2015). NWM commonly occurs in the months of DJF (Dec-Jan-Feb) and SEM in JJA (Jun-Jul-Aug).

The statistical results of wind and current data for the two monsoons can be seen in Table 2.

Table 1. Baseline simulation parameters for trajectory

No.	Parameter	Resolution	Source
1	Bathymetry	6 arc second	http://tides.big.go.id
2	Indonesia Map	-	https://gnome.orr.noaa.gov
3	Wind (U^{10})	3 hourly, 0.5°	NOAA/NCEP Global Forecast System (GFS) Atmospheric Model
4	Currents (-15 m)	Weekly, 0.3°	OSCAR Sea Surface Velocity
5	Windage	1–3 %	(Duhec et al., 2015)

Table 2. Statistical Data

Parameter	Wind (m/s)		Currents (m/s)	
	NW Monsoon	SE Monsoon	NW Monsoon	SE Monsoon
Min	0.0013	0.0010	0.0008	0.0006
Max	15.3574	13.6744	3.1433	3.1070
Mean	4.1658	5.1048	0.2952	0.2923
St. dev.	2.6355	3.1138	0.3682	0.3548

Under extreme conditions, the wind speed reaches up to 15.34 m/s in NWM with ocean current velocity up to 3.14 m/s. This speed has also been obtained in other studies (Rachmayani et al., 2018; Utamy et al., 2015) related to the circulation in Indonesia Seas and surroundings.

GNOME Model input dan Simulation

GNOME uses the standard Eulerian/Lagrangian approach to a model with regional physics. Then, simulated Lagrangian Elements (Les) is calibrated twice a day and forecasts are made for up to 3 days. GNOME utilized surface currents from the 1/12° operational HYCOM (Global Hybrid Coordinate Ocean Model) from the Naval Research Laboratory and 1/4° global wind product from the NOAA Blended Sea Winds. The complete description of the model and setting can be found in Maximenko et al., 2018. The methodology used for oil spills is sufficient for modeling floating plastic debris (Le Hénaff et al., 2012), where the floating plastic is assumed to have a velocity equal to the vectorial sum of the water currents and the wind drift velocities. The direct movement of plastics due to the wind (wind drift) was neglected in many previous studies (Isobe et al., 2009; Martinez et al., 2009; Kako et al., 2011; Reisser et al., 2013; Isobe et al., 2014; Maes and Blanke, 2015). GNOME wind drift (referred to as windage in GNOME) can be set manually to represent different types/scenarios of debris modeling.

Generally, the primary inputs to run a model in GNOME are currents, winds, and diffusion. In order to obtain the overall movement u (east-west) and v (north-south) velocity components from currents, wind, diffusion, and any other movers are added together in each timestep, using a forward Euler scheme (a 1st-order Runge-Kutta method). The movers are given a point (x,y,z,t) and return a displacement $(\Delta x, \Delta y, \Delta z)$ at t (Zelenke et al., 2012).

$$\Delta x = \frac{u}{\cos(y)} * \Delta t, \quad (1)$$

$$\Delta y = \frac{v}{112.120} * \Delta t, \text{ dan } \Delta z = 0$$

Where $\Delta t = t - t_1$ is the time elapsed between timesteps; y is the latitude in radians; 111.120 is the number of meters per degree of latitude (assumes 1° latitude = 1 nautical mile everywhere); and $(\Delta x, \Delta y)$ are the 2-D longitude and latitude displacement, respectively, at the given depth layer z . The authors used three-hour time-step and three-month simulation fit to the monsoon situation in SEA. The GNOME model was chosen because it requires low computing power with relatively high accuracy, especially in modeling open ocean debris transport (Maximenko et al., 2018). The model was run for two seasons: December to February represent Northwest Monsoon (NWM) and June to August represent Southeast Monsoon (SEM). The distribution display would be snapshot on the 15th for three months. The employed wind and current data are SEM in 2019 and NWM in 2020. The settings in GNOME were extrapolated with the first and last model values for movers and a 3-hr timestep. Three scenarios with different windage class were used to represent various types of debris found in the ocean based on how much they are submerged relative to the ocean surface (Duhec et al., 2015; Purba et al., 2019b). The three windage classes are as follows: 0–1% (low), 1–2% (medium), 2–3% (high) based on the previous research (Duhec et al., 2015; Zelenke et al., 2012). Examples of low windage litter are fishing nets, small plastic fragments and bottle caps; medium windage litter includes: polystyrene, foam sheet, PET bottle partially filled with seawater, and glass bottles; finally, high windage litter comprises: empty PET bottle and fishing buoys (Duhec et al., 2015). Afterwards, based on a GNOME expert, the settings for marine debris was done by adjusting its input such as non-weathering setting, the amount

released per station is 10 kg, and release time is every four days. The authors compared observational reports in several sites (Pangandaraan, Kuta, and Kupang) to help identify the regions reached by these litters.

RESULTS

From all kind of windage simulation, the models showed that MD spread to different trajectories from their initial positions. In the northern part boundaries, the areas that have a significantly large amount of coastal debris are Riau Archipelago, Western Borneo (parts of Malaysia also affected), Eastern Borneo (Transect B), North Maluku and Raja Ampat (Transect D and E). In the southern part of Indonesia, the areas that are significantly affected by marine debris are Aru Island, Babar Island, Sumba, Bali and western coasts of Java Island. Other areas outside of Indonesia that were affected are Malaysia, Timor Leste, Brunei Darussalam, Thailand, and Australia. A large amount of marine debris can be seen piling up along the coast of eastern Malaysia during SEM. On the other hand, the western part of Malaysia is mostly affected during NWM. Timor Leste, which is close to the initial release locations in the Arafura Sea, is affected by marine debris in both seasons.

Windage class 0–1%

Generally, the marine debris with windage below 1% has a different trajectory in each transect for both seasons (fig. 2). During NWM in the northern side, transect A, the debris was distributed towards the southeast (Malacca Strait) and the Indian Ocean. In December (orange dots), debris was spotted in the southern Malaysia, Indian Ocean, and Sumatra Island. Then, in January (green dots), it was discovered in the south of Malacca Strait and in December (orange dots), debris was spotted back around the starting points and in the southern part of the transect (Sumatra Island). The furthest spread of debris from this transect was 549 km (Indian Ocean) in February. Then, in the transect B, a lot of debris moved to coastal areas in the islands of the west and east (Indonesia, Malaysia, and Singapore) as well as the Bangka-Belitung Island.

Furthermore, it can be seen that in December (orange dots), debris was spotted in the eastern

part of Malaysia, Singapore, northern Natuna Seas, up to Brunei Darussalam. Some other debris also headed south towards Bangka Belitung Islands. In January (green dots), debris was spotted in Batam Island, Singapore, and north of the transect in the Indonesia – Malaysia border. The farthest debris distribution from this transect is 1,112 km in the Malaysian waters in January. In the Makassar Strait (transect C), debris spread to the north side, however not far from the initial point. In December (orange dots), debris was covered only around the starting points. In the next month (green dots), debris spread westward towards Kalimantan Island. Then, in February (pink dots), debris was seen on the coastline of Kalimantan Island. The farthest distribution of debris from this transect is 548 km on the shoreline of Kalimantan Island in February.

In transect D, generally, debris spread towards the Pacific Ocean and to the south of the transect area. In December (orange dots), debris was spotted in the southern waters of Seram Island and also seen in the northern side of the Pacific Ocean transect. In January (green dots) and February (pink dots), debris was seen on Morotai Island (northeast of transect D). The farthest debris distribution from this transect is 745 km in the Pacific Ocean in December. For transect E, debris spread to the beaches in the east and areas that were not far from the starting point. In December (orange dots), debris was seen in the western region of Papua Island, but still around the transect area. In January (green dots), debris was seen accumulating around the west part of Papua Island. In February (pink dots), debris was found in the southern of transect E in Seram Island. The farthest debris distribution from this transect is 158 km in the western Papua waters in February.

The areas in the southern region (outflow) also have a different pattern with the northern side and seasons. In general, during NWM, debris spread around the starting position and some more towards the south in transect F (Great Barrier Reef-Australia). In December (pink dots), debris spread towards the eastern and western part of the transect. In January (green dots), debris was more concentrated in the eastern and western part of the transect. In February (pink dots), debris was seen directed to the southern part of the transect. The farthest debris distribution from this transect is 1050 km in the western part of the transect in February.

In transect G, debris only spread around starting points. Debris was concentrated in Sumba Island, west of the transect. The farthest debris distribution from this transect is 123 km in the western part of the transect in February. In transect H (Lombok Strait), the debris spread to island surrounding. In December (orange dots), debris spread towards the eastern and western part of the transect. In January (green dots), debris was more concentrated in the eastern and western part of the transect. In February (pink dots), debris was seen spreading further with the highest concentration in the southern part of the transect. Debris also reached islands in the western part of the transect. The farthest distribution of debris from this transect is 110 km in February.

In the Sunda Strait (Transect I), debris spread to the western side of the straits and also to the coastal area in Sumatera island. In December (orange dots), debris was only seen on the eastern part of the transect (Java Island). In January (green dots), debris was more concentrated in the northern part of the transect but also seen near the maritime border in the Indian Ocean. In February (pink dots), debris was seen in the western waters of Sumatra Island such as in the Mentawai and Enggano Island. The farthest distribution of debris from this transect is 938 km in March.

During SEM in the northern side, transect A, the debris was distributed towards the southeast (Malacca Strait) and the Indian Ocean. In June (orange dots), debris were spotted in the southern part of the transect (Sumatra Island) and the Indian Ocean. In July and August, there was no debris detected, indicating that debris was already accumulated in the coastlines or outside the study area. The farthest debris distribution from this transect is 549 km in the Indian Ocean in August. Then, in transect B, a lot of debris moved to the coastal regions of the surrounding islands on the western side of Malaysia and Thailand Peninsula. In detail, it can be seen that in June (orange dots), debris were spotted around the transect and also in the eastern waters of Malaysia. In July (green dots), debris was seen in the South China Sea and off the coast of Thailand. In August (pink dots), debris was seen along the eastern part of Malaysia, Thailand, up to the South China Seas.

Debris was also spotted around transect B and in the Natuna Seas. The farthest debris distribution from this transect is 738 km in the South China Sea in August. In Makassar Strait (transect C) during the SEM, debris spread to different directions and was accumulated in the coastal areas (west and east of the transect). In June (orange dots), debris was seen at the southern part of the

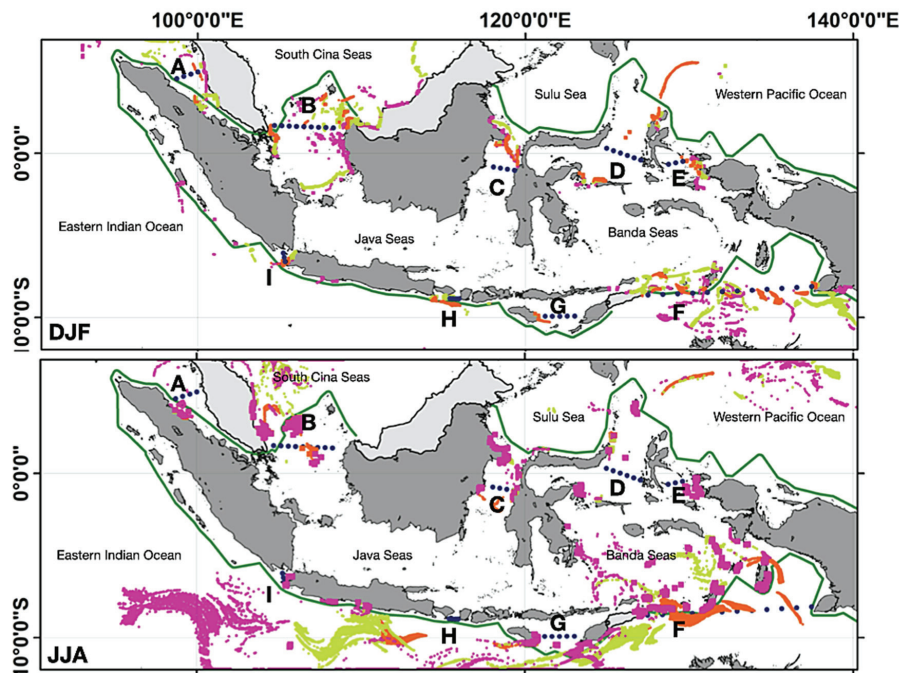


Figure 2. Marine debris trajectories in both seasons for Windage 0–1% overlaid with Indonesia maritime border (green line). Orange dots represent the trajectory positions on 15 December (A), and 15th June (B), green dots represent the trajectory positions on 15th January (A) and 15th July (B), and pink dots represent the trajectory positions on 15th February (A) and 15th August (B)

transect but not far away from the initial location. In July (green dots), debris was only spotted in the northern side of the transect. In August (pink dots), debris was spotted heading towards the northern part of the transect and also scattered around the coastal area of Sulawesi and Malaysia. The farthest debris distribution from this transect is 242 km in the Borneo Island in August.

In transect D, generally, debris spread towards the Pacific Ocean and to the southern part of the transect. In June (orange dots), debris was spotted in the northern part of the transect in the northern waters of Sulawesi Island. In July (green dots) and August (pink dots), debris was spotted in the western Pacific Ocean. The farthest debris distribution from this transect is 1560 km in the Pacific Ocean in August. For transect E, debris spread to the south of starting points. In June (orange dots), debris was spotted in the Aru Sea. In July (green dots), debris was covered accumulating in the Banda Sea. In August (pink dots), debris was seen reaching Transect E around the outflow water. The farthest debris distribution from this transect is 1270 km in the Ombai Strait.

The areas in the southern region (outflow) also have a different pattern with the northern side and seasons. In general, in transect F, during SEM, debris mainly spread to the west side up to the Indian Ocean. In June (orange dots), debris spread to the west of the transect. In July (green dots), debris was more concentrated in the waters of South Java. In August (pink dots), debris was spotted in the eastern Indian Ocean. Then in August, the debris from this starting point accumulated with the debris from other transects in the outflow water. The farthest debris distribution from this transect is 3105 km in August. The debris from transect G spread along with the debris from transect F. In June (orange dots), debris was spotted south of East Java. In July (green dots), debris was more concentrated around the pathway of ITF and southern Java waters. In August (pink dots), debris was seen up to the eastern Indian Ocean. The farthest debris distribution from this transect is 1808 km in the Indian Ocean in August.

In transect H (Lombok Strait), debris spread gradually to the eastern Indian Ocean. In June, (orange dots), there was no debris spotted near the transect, most of the debris was already located in the south of Java Island along with the debris from transect G, and F. The debris from this transect was found to be following the path of

ITF. In the Sunda Strait (Transect I), debris spread to the east side of the straits and also to the coastal area in Java island. Debris also spread to southern Java coast in Pangandaran in August (592 km).

Windage class 1–2%

In general, debris with 1–2% windage has a pattern that is almost similar to windage of class <1% (fig. 3). During NWM in the northern side, transect A, debris was distributed towards the southeast (Malacca Strait) and the Indian Ocean. In December (orange dots), debris was seen in the western part of Malaysia, Indian Ocean, and Sumatra Island. In January (green dots), debris was spotted in the Malacca Strait area and the northern part (Indian Ocean). In February (pink dots), debris spread to the Indian Ocean, western coast of Malaysia, southern coast of Sumatra, and south part of Malacca Strait. The farthest debris distribution from this transect is 728 km in the Indian Ocean in February. Then, in the transect B, numerous debris moved to the coastal areas in the islands of the west and east, affecting Indonesia and Malaysia. In detail, it can be seen that in December (orange dots), debris was circulating near Peninsular Malaysia, Malaysian Borneo, and northern Natuna. In January (green dots), debris was seen near the coastal area of western and northern Borneo Island. In February (pink dots), debris was seen stranded on several coastlines (Bintan Island, Batam Island, and Borneo Island). The farthest debris distribution from this transect is 882 km in the waters of Borneo Island in January. In the Makassar Strait (transect C), debris spread to the north but not far from the initial point. In December (orange dots), debris was seen extending to the eastern coast of Borneo and western coast of Sulawesi. In January (green dots), some debris was already found stranded on the coastlines of Borneo and Sulawesi. In February (pink dots), most of the debris was already stranded on the shoreline of Borneo and Sulawesi although some debris was still floating. The farthest debris distribution from this transect is 338 km on the coast of Borneo Island in February.

In transect D, generally, debris spread towards the Pacific Ocean and to the south of the transect. In December (orange dots), debris was seen in the Taliabu Island, east of Sulawesi, and some debris was also detected north of the transect in the Pacific Ocean. In January (green dots) and February (pink dots), debris was spotted

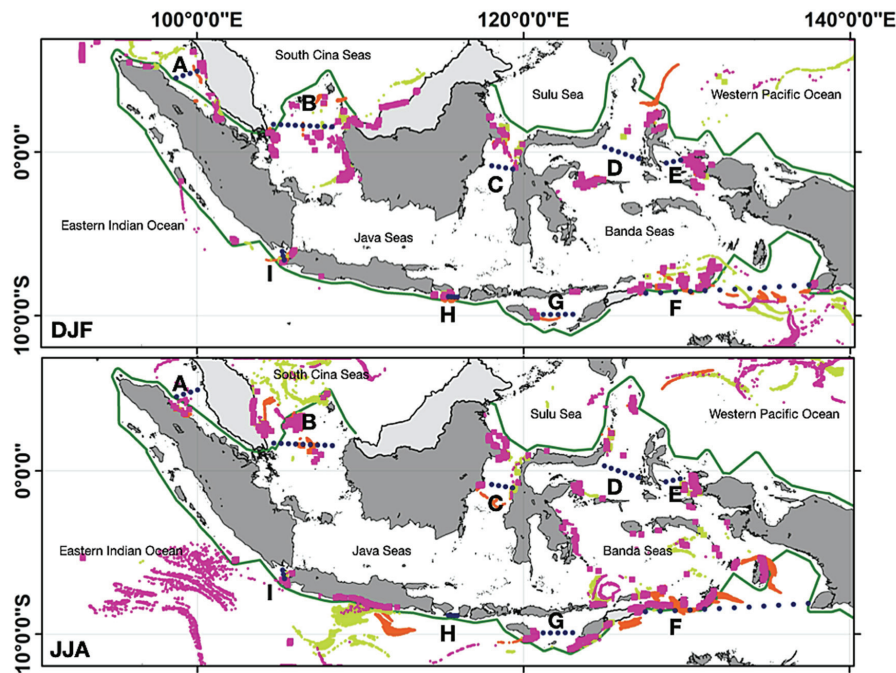


Figure 3. Marine debris trajectories in the two seasons for Windage 1–2% overlaid with Indonesia maritime border (green line). Orange dots represent the trajectory positions on 15th December (A), and 15th June (B), green dots represent the trajectory positions on 15th January (A) and 15th July (B), and pink dots represent the trajectory positions on 15th February (A) and 15th August (B)

stranded in the Morotai Island and some other debris were spotted floating in the Pacific Ocean. The farthest detected debris from this transect is 1,789 km in the Pacific Ocean in December. For transect E, debris spread to the beaches in the east and areas that were not far from the starting point. Debris accumulated in the western part of Papua from December to February. The farthest detected debris from this transect is 212 km in the west region of Papua in February.

The areas in the southern region (outflow) also have a different pattern and season with the northern side. In general, during NWM, transect F, debris spread to the north of starting position and some more towards the south (Great Barrier Reef-Australia). In December (orange dots), debris spread to the east and also to the west of the transect. In January (green dots), debris headed further south and north of the transect. In February (pink dots), debris was seen spreading to the Maluku Islands (Banda Sea), and some were distributed towards Australia. Some debris also ended up in the eastern part of the transect (Papua). The farthest debris distribution from this transect is 957 km in Arafura Sea/Australia in February.

In transect G, debris only spread around starting points. Debris was detected in the western part of the transect in Sumba Island. The farthest

debris distribution from this transect is 150 km in the west of the waters of the transect in February. In transect H (Lombok Strait), debris spread to the surrounding islands. In December (orange dots), debris spread to the southern and western part of the transect. In January (green dots), debris was more concentrated in the western part of the transect. In February (pink dots), debris was also more concentrated in the western part of the transect. In February (pink dots), debris was seen spreading towards the east of Bali Island and Java Island, and some ended up stranded on the island coastlines. The farthest distribution of debris from this transect is 124 km in the waters of southern Java in February.

In the Sunda Strait (Transect I), debris spread to the west side of the straits and also to the coastal area in Sumatera island. In December (orange dots), debris was only seen in the eastern part of the transect (Java Island). In January (green dots), debris was more concentrated in the northern part of the transect, but some was also found in the western waters of Sumatera Island (Indian Ocean). The farthest distribution of debris from this transect is 938 km in the Indian Ocean in February.

During SEM in the northern side, transect A, debris was distributed to the north and southwest of initial position (towards the Indian Ocean

– towards Sumatra Island). From June to August, most of the debris moved southwest towards Sumatra Island and ended up being stranded although some of the debris also moved northwards towards the Indian Ocean. Then, in the transect B, plenty of debris moved to the coastal areas in Peninsular Malaysia. In detail, it can be seen that in June (orange dots) debris was seen in the middle part of the transect and also in the waters of eastern Peninsular Malaysia. In July (green dots), most of the debris moved further northwards towards Thailand and some headed west towards the coast of Peninsular Malaysia. In August (pink dots), most of the debris ended up either in the eastern coast of Peninsular Malaysia or further north in the northern part of South China Sea. The farthest debris distribution from this transect is 665 km near the Gulf of Thailand. In the Makassar Strait (transect C) during the SEM, debris spread mostly towards the coastline of Sulawesi Island and Borneo Island. In June (orange dots), most of the debris was still floating and headed towards the south of starting points, although some was already stranded. In July, (green dots), most of the debris was already stranded on the coastlines of Borneo and Sulawesi. In August (pink dots), the debris previously stranded on Sulawesi coastline moved towards Borneo and mostly ended up in the island's northern coastline. The farthest distribution of debris from this transect is 360 km in the Indian Ocean in February.

In transect D, generally, debris spread towards the Pacific Ocean and to the south of the transect. In June (orange dots), debris were spotted in the northern part of the transect (Sulawesi Island), and some were even detected in the Pacific Ocean. In July (green dots) and August (pink dots), debris was seen in the western part of the Pacific Ocean. The farthest debris distribution from this transect is 127 km in the Pacific Ocean in August. For transect E, all of the debris spread to the eastern side to the southeast of starting points. Debris reached West Papua on June and was only transported to the islands near the starting points. The farthest debris distribution from this transect is 127 km in the coastline of West Papua.

The areas in the southern region (outflow) also have a different pattern with the northern side and seasons. In general, during NWM, in transect F, during the SEM, debris mainly spread northward towards islands in the Maluku province. In June (orange dots), debris spread northward

towards Maluku islands, but most are still floating. In July (green dots), some debris moved further northward towards Ambon and Sulawesi, and some debris was already stranded on the coastlines of adjacent islands north of the starting points. In August (pink dots), the majority of the debris was already stranded on the shoreline of adjacent islands north of the transect and reaching as far as the coastline of eastern Sulawesi. The farthest debris distribution from this transect is 1316 km on the east coasts of Sulawesi island. In transect G, debris mostly spread to the west of the starting points, and some were stranded in Sumba Island. In June (orange dots) some debris was already stranded on the coastline of Sumba Island and some were still floating and heading further west of the starting points. In July (green dots), debris headed further east, located in the south of the Java island. In August (pink dots), debris was spotted further west, in the eastern Indian Ocean/Southwest of Sumatra Island. The farthest debris distribution in this transect is 2546 km in the Eastern Indian Ocean in August.

In transect H (Lombok Strait), all the debris spread westward towards the Indian Ocean along with the debris from transect G, and none was stranded near the starting points. The trajectory of debris in this transect was also found to be similar to the pattern of ITF. The farthest distance of debris distribution from this transect is 2049 km in the eastern Indian Ocean. In Sunda Strait (Transect I), debris spread to the east side of the straits and also to the coastal areas in Java island. Debris only moved around the coastal regions from June to August and did not spread far away from the initial location.

Windage class 2–3%

The debris with 2–3% windage generally has a similar pattern to the previous windage classes (fig. 4). During NWM in the northern side, transect A, the debris was distributed towards the southeast (Malacca Strait) and the Indian Ocean. The farthest distance of debris distribution on this transect is 732 km in the Indian Ocean, in February. Then, in transect B, the majority of the debris ended up on the coastline of Malaysian and Indonesian Borneo, Riau Archipelago and Bintan Island. The farthest distribution of debris on this transect is 667 km on the coast of Malaysia, Borneo, namely in January. In the Makassar Strait (transect C), debris spread northwest and

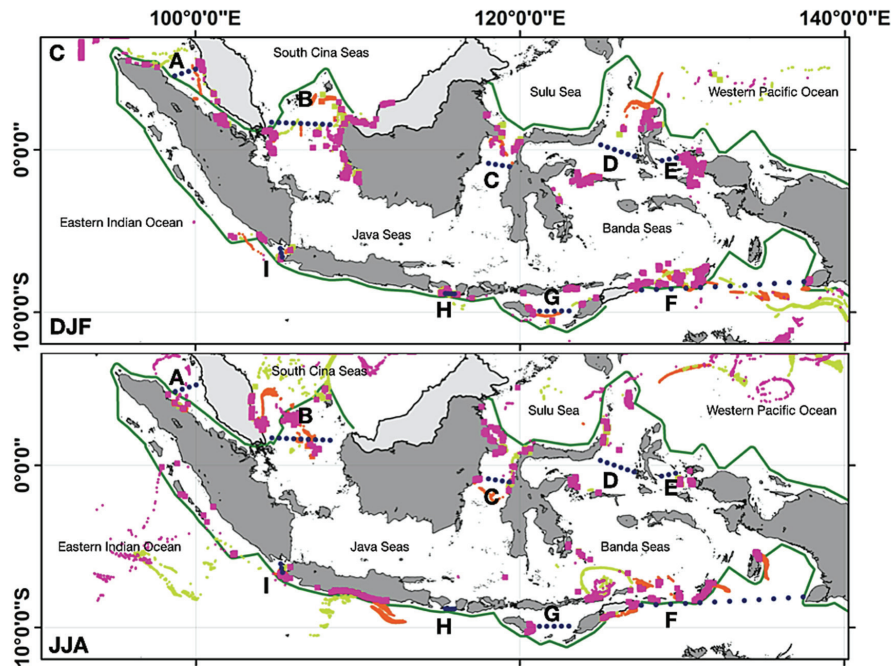


Figure 4. Marine debris trajectories in the two seasons for Windage 2–3% overlaid with Indonesia maritime border (green line). Orange dots represent the trajectory positions on 15th December (top), and 15th June (bottom), green dots represent trajectory positions on 15th January (top) and 15th July (bottom), and pink dots represent the trajectory positions on 15th February (top) and 15th August (bottom)

northeast gradually and eventually ended up on the adjacent coastline of Sulawesi and Borneo. The farthest distance of debris distribution on this transect is 354 km, which is on the coast of Borneo Island in February.

In transect D, generally, debris spread north towards the Pacific Ocean and to the south of the transect towards Sulawesi and Taliabu Island. The furthest distance of debris distribution on this transect is 1794 km in Pacific Ocean waters, namely in December. For transect E, debris spread to the beaches in the east and areas that were not far from the starting point. Debris accumulated in the western part of Papua from December to February. The furthest distance from the distribution of debris on this transect is 321 km in the waters west of Papua, namely in February.

The areas in the southern region (outflow) also still have a different pattern with the northern side. In general, during NWM, transect F, the debris from the western part of transect moved towards the north (Maluku Islands), and the debris from the eastern part of the transect moved southwards, towards Australia. A certain amount of the debris also ends in the east of part of the transect in Papua. The furthest distance of debris distribution on this transect is 966 km in Arafura/northern Australia waters in February.

In transect G, debris only spread around the starting points. Debris is seen on the western side of the transect on the island of Sumba from December to February. The furthest distance of debris distribution on this transect is 178 km in western waters, namely in February. In transect H (Lombok Strait), the debris spread to the adjacent islands (Bali and Lombok) and ended up stranded on the island coastlines at the end of the modeling. The furthest distance from debris distribution on this transect is 59 km off the coast of Bali island in February. In the Sunda Strait (Transect I), debris spread to both the west and east side of the transect, reaching the coastline of Java and Sumatra island. In December (orange dots), debris initially moved to two directions, towards the Indian Ocean and the coast of the Java Island. In January (green dots) and February (pink dots), debris was seen stranded on the coastlines of Sumatra and Java.

During SEM in the northern side, transect A, the debris was distributed to the north and southwest of initial position (towards the Indian Ocean – towards Sumatra Island). From June to August, most of the debris moved southwest towards Sumatra Island and ended up being stranded although some of the debris also moved northward towards the Indian Ocean. Then, in transect

B, more debris moved to the coastal areas in Peninsular Malaysia. In detail, it can be seen that in June (orange dots), debris was seen around the middle transect and also on the east coast of Malaysian waters. In July, (green dots), most of the debris moved further northward towards Cambodia. Next, in August (pink dots), most of the debris ended up either in the eastern coast of Peninsular Malaysia or further north in the northern part of South China Sea. The furthest distance of debris distribution on this transect is 623 km in the northern part of South China Seas, namely in August. In the Makassar Strait (transect C) during SEM, debris spread mostly towards the coastline of Sulawesi Island and Borneo Island and ended up stranded on the island coastlines. The farthest distance of debris distribution on this transect is 529 km, namely on the coast of the island of Borneo in August.

In transect D, debris generally spread towards the Pacific Ocean and to the south of the transect. Debris gradually spread from the starting points to the Pacific Ocean and Sulawesi Island. Eventually, some debris ended up stranded on the coastline of the Sulawesi Island. The furthest distance of debris distribution on this transect is 1721 km in Pacific Ocean waters, namely in August. For transect E, the debris spread to the east – southeast of the starting points. Debris reached West Papua on June and was only transported to the islands near the starting points. The distribution of debris on this transect is 148 km on the coastline of West Papua.

The areas in the southern region (outflow) also have a different pattern with the northern side and seasons. In general, in transect F, during SEM, debris mainly spread northward towards the islands in the Maluku province. The majority of the debris ended up stranded on the coastline of adjacent islands, north of the transect, and reaching as far as the coastline of eastern Sulawesi (1089 km). In transect G, all the debris ended up stranded in the adjacent Sumba Island (164 km). In transect H (Lombok Strait), all the debris spread westward towards the Indian Ocean along with the debris from transect G, and none were stranded near the starting points. There is also a large amount of debris found stranded in the southern coast of Java Island coming from this transect. The furthest distance of debris distribution from this transect is 2526 km in the eastern Indian Ocean. In the Sunda Strait (Transect I), debris spread to the southern side of the straits and

also to the western coastal area in Java island. Debris only moved around the coastal regions from June to August and did not spread far away from the initial location (60 km).

DISCUSSION

From the results, it can be shown that almost all beaches in the borders between countries are affected by marine debris. Debris spread not only on beaches, but also to the open ocean such as the Indian Ocean and the Pacific Ocean. Debris accumulation occurred in islands or coastal areas in the northern region (inflow) such as East Sumatra, West Kalimantan, North Sulawesi and North Maluku. In the outflow region, litters build-up in Aru Sea, Lombok Strait and Sunda Strait. Other countries affected by marine debris, as shown by this study, are Thailand, Malaysia, Singapore, Brunei Darussalam, Timore Leste, and Australia. Generally, the spread of MD in all areas seem to follow the monsoon currents. The average current speed in the Indonesian waters is between 0.001 – 2.93 m/s (fig. 5).

From the results, it can be observed that the spread of MD with windage of 0–1% and 1–2% looks more similar when compared to windage 2–3% both during NWM and SEM. The difference in trajectory is directly related to the windage, where the debris with higher windage is less submerged; therefore, it is more affected by the wind. The wind velocity in the Indian Ocean near the equator is smaller than any other place in the area (<0.5 m/s)(Rachmayani et al., 2018). The debris trajectory on the ocean surface is affected by the wind and current, where the ocean currents direction is not always exactly parallel to the wind direction, vice versa.

Then, Pearson correlation was carried out to find the correlation of wind movement with ocean currents in the inflow area (A-E). There is a strong correlation in transect B (Natuna Sea) and D (Maluku Sea) during NWM. Pearson correlation shows a low correlation between wind and currents in all transects in the outflow area. It was quite strong in the inflow areas, especially in transect B except in transect D, it was strongly negatively correlated (fig. 6).

In the Malacca Strait (Transect A), debris distribution was the same as the current pattern that follows the strait contours. The ocean current from IO and Malacca Strait cause different

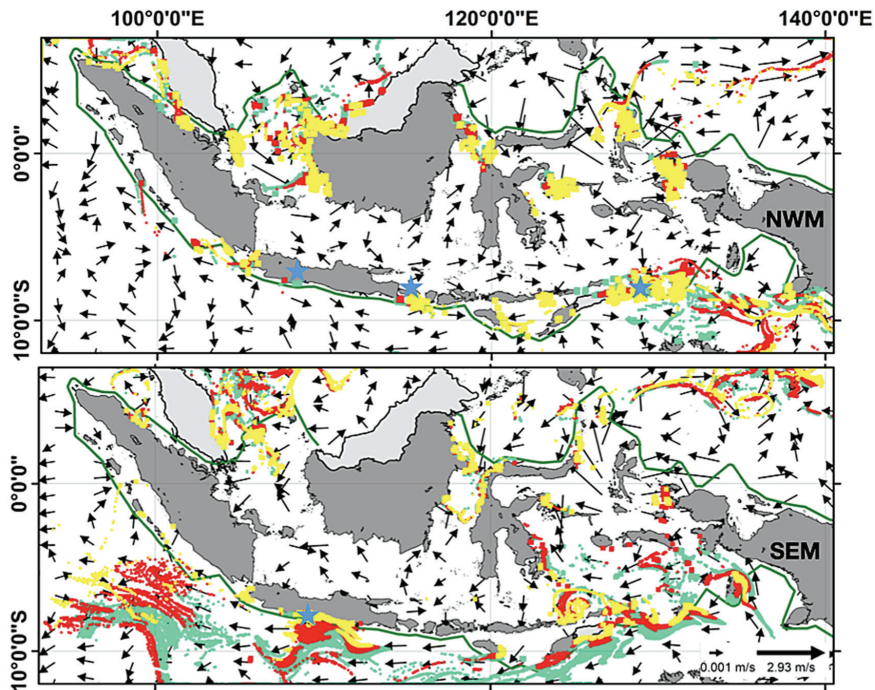


Figure 5. Marine debris trajectory overlaid with ocean currents in a different season. (blue) 0–1% windage, (red) 1–2% windage, (yellow) 2–3% windage, and the blue star is field data from Attamimi et al. (2015); Purba et al. (2019); Hiwari et al. (2019).

debris trajectory in the two monsoons. The ocean current in the NWM is visibly more robust than the ocean currents velocity in the SEM. In the NS (transect B), the ocean currents are similar to the monsoon pattern. This ocean current pattern was also previously mentioned in Apriansyah and Atmadipoera (2020). In NWM, strong winds from the north caused southward current and carried

debris to the western part of Borneo, Peninsular Malaysia, and Singapore. In SEM, the winds from the southeast force water mass and subsequently debris northward. This pattern can be seen by the higher concentration of debris in the South China Sea and off the coast of Thailand. Furthermore, anticyclonic eddies also occur in this area in which the occurrence of eddies depends on the

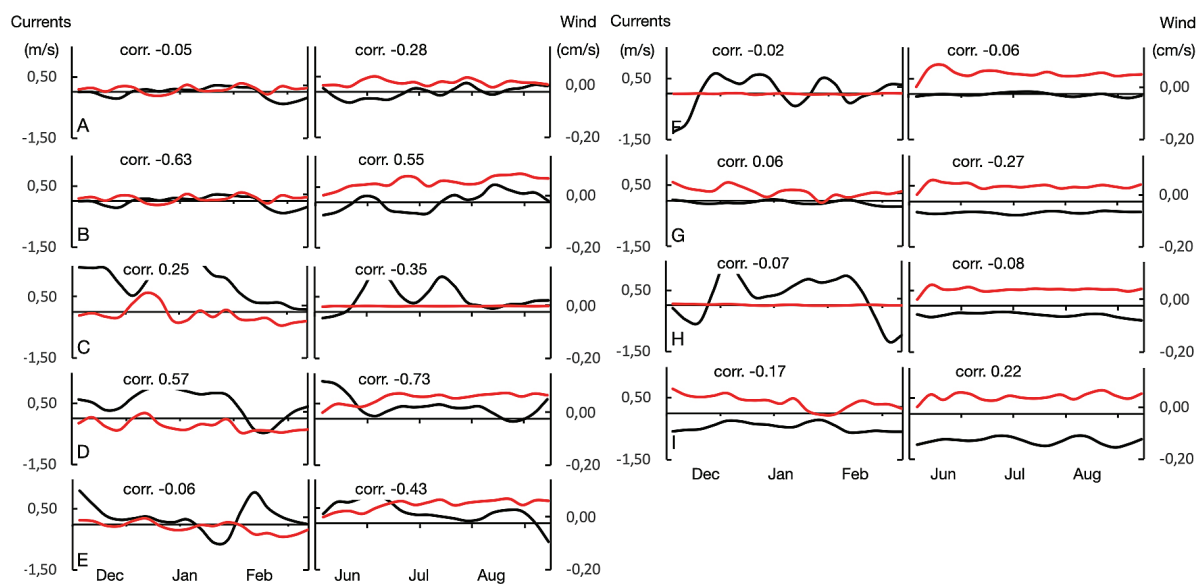


Figure 6. Meridional wind and currents in each transect in NWM (left) and SEM (right)

monsoon. This occurring eddies carried the debris towards adjacent islands and coasts such as Borneo and Peninsular Malaysia due to the contour of the islands.

Therefore, the currents crossing transect C-E differ as they originated from different sources (Morey et al., 1999) and were influenced by local currents in their paths (Wang et al., 2019). In general, the dominant wind and current came from the north where the pattern began to shift towards the south in the early transition season. In transect C (Makassar Strait) and D (Maluku Sea), a uniform pattern occurred during NWM because their locations were the entrance of ITF that flows all year long that is amplified in the SEM (Gordon et al., 2012). In this context, debris was seen accumulating in the southern part of the transect in NWM and further south in the SEM. In Transect E (Halmahera Sea), there are differences in patterns due to local sea currents around the small islands (Wang et al., 2019). The ocean current condition in this area is affected by ITF that flows through the northern region of Papua, Halmahera Eddies (HE), and Mindanao Eddies (ME) that is connected with the North Pacific Gyre (Nugraha et al., 2018; Oka et al., 2018). The current movement patterns varied in SEM due to counter currents direction of the dominant current coming from the south. The debris in this area was carried to the Pacific by HE and ME. Previous studies (Maximenko et al., 2012; Van Sebille et al., 2012) have found that floating marine debris tends to accumulate mainly in the subtropics. In the other monsoon, the ocean current pattern was dominated by the southward current, and debris accumulation was seen around the Aru waters. The previous research conducted by Ramos et al. (2018) indicated that this area is also an entrance for the debris coming from the Pacific. This debris presumably comes from the Pacific and the adjacent islands. The result also showed that the debris particles from the transect D and E would move towards Australia and the Indian Ocean via Banda and Aru Seas. This can be seen in the SEM when ITF is the strongest. In 3 months, debris was spotted around the southern Java area.

In the transect F, there were variations in the current movement in which it moved from the north and south during NWM because the dominant current came from the Northwest side. However, transect F was also the primary path for the flowing current from the south which resulted in a pattern variation (Waterhouse et al., 2013).

In NWM, the debris from this transect was seen spreading towards the east and west of the transect due to the ocean current. In SEM, debris was spotted reaching as far as the Banda Sea. This is due to the strong wind condition from Australia and also ITF that caused debris to be transported to IO. Furthermore, during NWM, transect G (Savu Sea) has a constant current movement and medium speed because it was located on an island of the northern area. The debris in this area was also seen around the transect. This is because this area is constructed by plenty of islands; therefore, debris tends to become stranded in the islands' coastlines. In SEM, this area is also the main pathway for ITF (Apriansyah and Atmadipoera, 2020). In this area, the ocean current tends to head towards the IO.

Furthermore, in the NWM, (Hiwari et al., 2019) modeled the microplastic pathways near the transect G and found that the microplastic conditions drifted to the southern waters which are following the ocean currents situation in the diagram. In SEM, the research conducted by (Purba et al., 2018) discovered that most of the debris found on the beach were plastics and foams and came from the north side. It is similar to the ITF pathways that flow from Banda Seas to the Indian Ocean via Savu Seas (Transect G). In transect H (Lombok Strait), the current predominantly came from the north based on the main current path of ITF where the water entering Makassar Strait exit through Lombok Strait (Fieux et al., 1996; Sprintall et al., 2003). In NWM, debris was concentrated around the transect, but in SEM debris was transported towards IO. In the adjacent island, a research conducted by (Attamini et al., 2015) in Bali (fig 5. Top) found that there was a lot of litter at Kuta beach from December to February. Tourists often refer to it as "Holiday in Hell". On the basis of diagram during NWM, the debris accumulated in the southern area and the surrounding island. It was caused by the winds blowing from the west, forcing the marine debris to head towards the beach parallel on the east. The condition during the NWM is less affected by the weakening ITF and is more influenced by the stronger South Java Current (SJC) and winds (Molcard et al., 1996). In this case, the difference between scenario 1, 2, and 3 is the amount of coastal litter in South Java. When the amount of floating and coastal debris were compared, the lower windage debris seemed to be transported farther from South Java and towards the Indian Ocean.

Conversely, most of the debris with higher windage (scenario 3) ended up in South Java coasts. This seems to be in accordance with a simulation conducted by Duhec et al., (2015), which found that the marine debris transported from South Java to Western Indian ocean are mostly at low windage (1%). In contrast, higher windage (3%) debris contributed less to the marine debris abundance in the Western Indian Ocean. Transect I (Sunda Strait) had a dominant current from the south even though it was during NWM. This is because it was close to the Indian Ocean. Therefore it was mostly influenced by the ocean currents in the southern regions such as the SJV (Molcard et al., 1996). In other coastal areas located in Java Island, Purba et al., (2018a) stated that there was a debris shipment in Pangandaran (around 108° E) which originated from the surrounding river that was dragged by the sea current along the coast from the west side. Uniform wind and current patterns which occurred during SEM, where the dominant pattern from the south and the highest current velocity transpired, occurred in transect I.

Therefore, based on the debris pathways and ocean circulation, it can be seen that spreading of MD in south Java is interesting. The south Java waters are one of the complex circulations in Indonesia (Utamy et al., 2015). In this area, there are three main currents exist over the year: ITF, South Java Currents (SJV), and Leeuwen currents. In the southern regions of Java and Bali (around 10 S), debris distribution followed the eddies' pattern. This is seen during SEM with 0–2% windage. In this area, mesoscale eddies occurred due to the intersect of ocean currents from ITF and South Java Currents (SJV) (Tussadiah et al., 2016; Utamy et al., 2015;). In this monsoon, ITF has a stronger current than the other monsoon. The marine debris in the southern outflow gathered and merged towards the Indian Ocean. These simulation results, particularly for the south Java area, is similar to other simulations such as <http://plasticadrift.org> where we simulated nearly all transects, and it has a similar trajectory, especially in the southern regions.

CONCLUSIONS

The marine debris from the Indonesian boundary seas can be transported to the adjacent coastal areas or float in the ocean for several

months. MD reached at beaches before the 15th day. This shows that litter spread very fast in the seas of Indonesia and its surroundings. On the basis of the model, adjacent countries like Malaysia and Australia can be negatively impacted by the marine debris from Indonesia. Monsoonal winds were proven to have a significant impact on the distribution of marine debris. Different monsoons can affect the floating marine debris. This is due to the interaction between the debris floating on the ocean surface with the wind conditions. Furthermore, the shape of the Indonesian archipelago resulted in slowing down the transport of marine debris and act as a “filter” for the marine debris movements. This result also showed that Indonesian Seas do not only act as a debris accumulation spot for the debris coming from other countries but also the source of marine debris in the Pacific and the Indian Ocean.

The GNOME model proved to be a helpful tool in understanding the complexity of marine debris in Indonesian waters. It represents baseline information about the behavior of marine debris in the ocean when coupled with ocean currents and wind as the main driving forces. The waste management efforts, especially in the areas with minimum observation data, can benefit from this kind of simulation as it provides science-based information at a minimal cost. In future studies, a nation-wide or more extensive marine debris simulation can be significantly improved by using a more accurate observation data. An effective observation method for complex oceanic regions needs to be developed to create appropriate policies to help overcome the global marine debris issue.

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