Stable Carbon Isotope Signature of Particulate Organic Matter in the Southwestern Sumatran Waters of the Eastern Indian Ocean

A'an J. Wahyudi[1,*], Afdal[1], and Hanny Meirinawati[1]

[1]Research Center for Oceanography, Indonesian Institute of Sciences, Pasir Putih 1, Ancol Timur, Jakarta 14430, Indonesia
[*]Corresponding author: aanj001@lipi.go.id

ABSTRACT The Southwestern Sumatran Waters of the Eastern Indian Ocean are known to be affected by the South Java Current and the South Equatorial Counter Current. Many studies have been carried out in relation to upwelling and the Indonesian Through Flow. However, there has been no systematic study into the properties of the particulate organic matter in the Southwestern Sumatran Waters. Therefore, the organic matter in these waters in terms of its origin is unknown. As part of the *Ekspedisi Widya Nusantara* 2015 research cruise, this study aimed to examine the stable isotope δ^{13}C signature of particulate organic matter (POM), especially with regards to the origins of the organic matter. The stable isotope δ^{13}C is complemented by other variables such as chlorophyll-*a*, particulate organic carbon (POC), and nutrients (phosphate, silicate, ammonium and nitrate). The POC tends to be depth-dependent. The values of δ^{13}C are –23.56, –24.30, and –24.06‰ for 5, 100 and 300 m depths, respectively. We found that POM tended to be isotopically lighter with increasing POC and chl-*a*, especially in the surface water, potentially due to the preferential lighter carbon isotope for metabolism by the primary producer. The origin of POM in the Southwestern Sumatran waters is marine end-member in the surface (up to 100 m depth) and mixed compositions at the surface of twilight zone (100–300 m depth). The next layer, i.e. twilight zone (more than 300 m depth), is terrigenous end-member. The surface POM of SSW, as shown in 5 m depth, is not freshly produced and tends to be either autochthonous or allochthonous.

1. INTRODUCTION

The Southwestern Sumatran Waters (SSW) are located in the eastern Indian Ocean (EIO). This area is affected by both the South Java Current (SJC) and the South Equatorial Counter Current (SECC) (Schott et al. 2009; Hood et al. 2011). According to the global current pattern, these two main currents in the EIO, are affected by the monsoon (Susanto et al. 2001; Hood et al. 2011). Furthermore, the Southwestern Sumatran waters have been known as an area which is affected annually by upwelling. The upwelling in the EIO occurs along the island chain from Sumatra, Java, Bali, Lombok, Flores to Alor, during the southeast monsoon period (Susanto et al. 2001). The cool temperature signal of the upwelling firstly occurs east of the island of Lombok (April–May). Then, it proceeds westward along the southern Java waters, up to the Sunda Strait (late June), and then flows northwest into the western Sumatra waters (early August). Then, the retreat of the upwelling is very rapid and simultaneous across the whole island chain in October (Susanto et al. 2001; Yu et al. 2016).

Many studies about the chemical profile and characteristic of the particulate matter, solid organic ligand, and others, have been done (e.g. Hirose and Tanoue 1998; Boyd et al. 1999; Hirose et al. 2011). For instance, Boyd et al. (1999) suggested that the upper water column is characterized by two days turnover of particulate organic carbon (POC) and

a low but constant downward flux of POC. Studies by Hirose and Tanoue (1998) and Hirose et al. (2011) suggest that the increasing of the POC level with depth is followed by the decreasing of the concentrations of the strong organic ligand in particulate matter. Profile of those chemical constituents shows unique vertical distribution along the water column, where the maximum concentration is at the surface and gradually decreases with depth. The vertical profile of particulate organic matter (POM) (between 100–1000 m depth) shows a biogeochemical process, especially the sinking of materials produced by plankton in the euphotic layer (Hirose et al. 2011). This means that the vertical profile of POM is also closely related to the export vertical flux of the particles (Hirose and Tanoue 1998).

There has been limited studies about POM spatial distribution and its isotopic profile, especially in maritime continent areas (the Indonesian archipelago). Isotopic profile of POM is one of the important parameters to determine the origin of POM materials. Materials origin of POM itself is important for understanding the dynamics of biological pump such as POM's aggregation–disaggregation and fragmentation (Cavan et al. 2017). POM production may not be uniform since it is site and depth-dependent (Sarma et al. 2014), that condition imply the POM composition should be understood thoroughly. Other studies of POM and its isotopic profile have been conducted in the southwestern Atlantic (Lara et al. 2010), South China Sea (e.g. Liu et al. 2007a;

Kaiser et al. 2014), or the Danshuei estuary of the northern Taiwan (Liu et al. 2007b). Both POM and nutrients are important components in the biogeochemical process such as the biological pump (Liu et al. 2007b; Lara et al. 2010; Hirose et al. 2011), especially in the zone which is affected by both the SJC and the SECC currents, such as the SSW.

In a region with the dual current affection, the SSW have high opportunities in organic matter mixing due to the dual current itself or the upwelling event. Considering this physical characteristic, it means that the POM origin in this area is important and should be further investigated. One of the approach is using stable isotope signature.

Stable isotope signatures, especially carbon and nitrogen, are widely used for identifying the properties of water mass including the organic matter inside (e.g. Otero et al. 2000; Hwang et al. 2013; Kaiser et al. 2014), or the organic matter origin (e.g. Liu et al. 2007a; Lara et al. 2010). Besides the organic matter origin, stable isotope signatures can be used alongside the nutrient properties of the seawater (i.e. nitrate, phosphate, ammonium) to elucidate the variations of $\delta^{13}C$ properties (Lara et al. 2010). This kind of data is useful for analyzing both the material and the nutrient mixing during physical processes in the region, such as the upwelling.

This study aims to evaluate the stable isotope $\delta^{13}C$ signature of POM, especially in terms of understanding the organic matter origin. We also investigate the factors that contribute to $\delta^{13}C$ variability such as chl-a (as the phytoplankton biomass indicator) and nutrients.

2. MATERIALS AND METHODS

2.1 Field sampling

Conductivity, temperature and depth (CTD) instruments were deployed at 26 sites covering areas in the Sunda Strait, the Enggano Waters and the SSW (Figure 1). However due to the technical reasons, the water sampling was conducted only at 21 sites as shown in Table 1. The sampling was conducted during *Ekspedisi Widya Nusantara* (E-WIN) 2015 research cruise starting from Jakarta to Padang on 7–18 May 2015 (see Wahyudi et al. (2015) for details information

tion about E-WIN 2015). Water samples were taken using a rosette sampler that was deployed together with the CTD instruments. Water samples were taken at 5, 100, 200, 300, and 1000 m depth (2n per depth). The study site covered 200 to 4500 m of water depth.

2.2 Stable isotope analysis of POM

Sea water (1.0 L) was filtered into the Whatman GF/F glass fiber filter (D 25 mm). The filtrate was acidified to remove inorganic carbon using HCl fume for 1 min and neutralized by placing it in a vacuum desiccator with concentrated NaOH for 24 h. The dry weight was measured after oven drying at 60℃ up to constant weight.

Each filtrate sample (in glass fiber filter GF/F) was then packed into a tin capsule (Lüdiswiss Sn 98, d 9/10 mm). Further analysis was conducted using an Isotope Ratio Mass Spectrometer (IRMS) i.e. Thermo Delta Plus XP coupled to a trace GC ultra with a combi PAL autosampler. The analysis was conducted at Iso-trace Research, University of Otago (New Zealand).

The stable isotope ratios of $^{13}C/^{12}C$ are expressed as $\delta^{13}C$. The isotopic ratios were normalized using Pee Dee Belemnite (PDB). Isotope ratio (R) calculation, given as per-million (‰) deviation from the standard value ($\delta^{13}C$), where (Equation 1):

$$R = {}^{13}C/{}^{12}C \tag{1}$$

and (Equation 2):

$$\delta^{13}C(‰) = ((R_{sample}/R_{standard}) - 1) \times 1000 \tag{2}$$

TABLE 1. Rosette sampler deployment for water sampling altogether with CTD.

Site	Chl-a	Nutrient	POM
St6	5, 50, 100, 200 m	NA	5, 100, 300 m
St7	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St9	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St10	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St11	5, 50, 100, 200 m	NA	5, 100, 300 m
St13	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St14	5, 50, 100, 200 m	NA	5, 100, 300 m
St15	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St18	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St19	5, 50, 100, 200 m	NA	5, 100, 300 m
St20	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St23	5, 50, 100, 200 m	5, 25, 100 m	5, 100, 300 m
St24	NA	5, 25, 100 m	NA
St25	5, 50, 100, 200 m	NA	NA
St28	5, 50, 100, 200 m	NA	5, 100, 300 m
St29	5, 50, 100, 200 m	NA	5, 100, 300 m
St30	5, 50, 100, 200 m	NA	5, 100, 300 m
St31	5, 50, 100, 200 m	5, 25, 100 m	NA
St32	5, 50, 100, 200 m	5, 25, 100 m	NA
St33	5, 50, 100, 200 m	NA	NA
St34	5, 50, 100, 200 m	NA	NA

Note: Rows 2–4 represent the kinds of samples that were obtained during the cruise. Chl-a is for chlorophyll-a, nutrient is for macro-nutrient (phosphate, nitrate, ammonium and silicate), POM is for particulate organic matter.
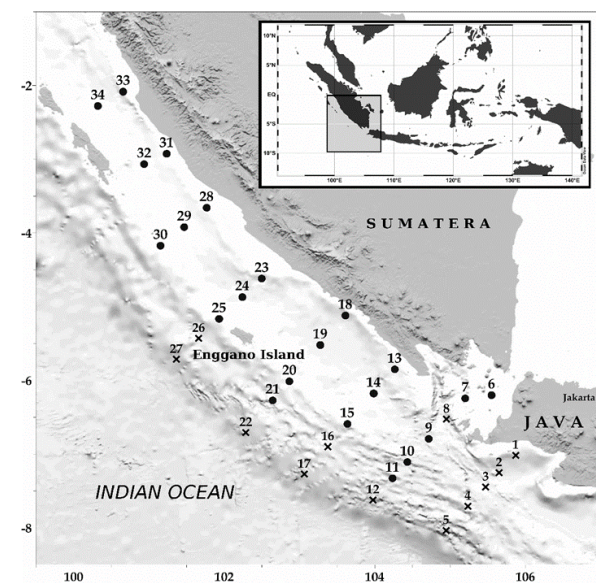

FIGURE 1. Study site in Eastern Indian Ocean. Filled circle (●) is the site where the CTD was deployed. The X is the planned site that due to the bad weather, the vessel could not reach those sites.

The isotopic and elemental values were determined using laboratory reference materials (USGS-40 and USGS-41). Control materials were used to determine precision and accuracy, namely EDTA-OAS and IAEA-414:Algae. Detailed information for stable isotope analysis and the usage of those references can be found in, e.g., Post (2002), Jacob et al. (2005), Lara et al. (2010), Carter et al. (2011), and Wahyudi et al. (2013).

2.3 Analysis of nutrient and chlorophyll-*a*

Water samples were taken representing three depths (i.e. 5, 100 and 300 m, respectively). About 500 mL seawater was extracted from the rosette sampler to a polyethylene bottle. The water sample was filtrated using nitrocellulose 0.45 µm. The nutrient was analyzed using spectrophotometric methods (Shimadzu UV-1201V) with wavelengths 885, 543, 630 and 810 nm for phosphate, nitrate, ammonium, and silicate measurement, respectively. Phosphate was analyzed according to the formation of the molybdate blue complex, according to the methods used by Murphy and Riley (1962), which were later modified by Strickland and Parsons (1972). Nitrate was analyzed as nitrite using reduction in the cadmium-cuprum column and reacted using sulfanilamide according to the methods used by Parsons et al. (1984). Meanwhile, for nitrite concentration measurement, the methods were similar to nitrate measurement without the reduction processes. Both ammonium and silicate were measured using the standard methods employed by Strickland and Parsons (1972). Meanwhile, the measurement of chlorophyll-*a* was conducted using fluorometric methods according to Cochlan and Hendorn (2012).

Analysis for nutrient and chlorophyll-*a* was analyzed from all sampling depth, except 1000 m. Further, since the IRMS could not detect the δ^{13}C of this depth (probably due to the amount of water samples), the later analysis to determine the POM profile in 1000 m depth used secondary data instead.

2.4 Statistics

Normal distribution was a priori checked using the Shapiro-Wilk normality test. Data were then compared using Analysis of Variance (ANOVA) complement with Tukey contrast were performed (α = 0.05; CI 95%), while non-normal distribution data were analyzed using the Kruskal-Wallis rank sum test (α = 0.05). All statistical analysis was performed using R version 3.4.2.

3. RESULTS

The water temperature and salinity of sampling sites has typical tropical water characteristics. The lowest surface water temperature was recorded in the Sunda Strait (29.5°C), while the highest temperature is near the equator (30.3°C). Seawater salinity ranges from 32.8 to 33.8 psu. The chl-*a* value of the surface water (5 m depth) is relatively lower than the chl-*a* value of the 100 m depth water-mass. However, the Kruskall-Wallis rank sum test verifies that there is no significant difference among chl-*a* collected from different depths (χ^2 = 1.03, df = 1, *p*-value = 0.31).

Particulate organic carbon (POC) concentrations shows a significant difference over different water depth (Kruskal-Wallis rank sum test chi-squared = 16.1283, df =
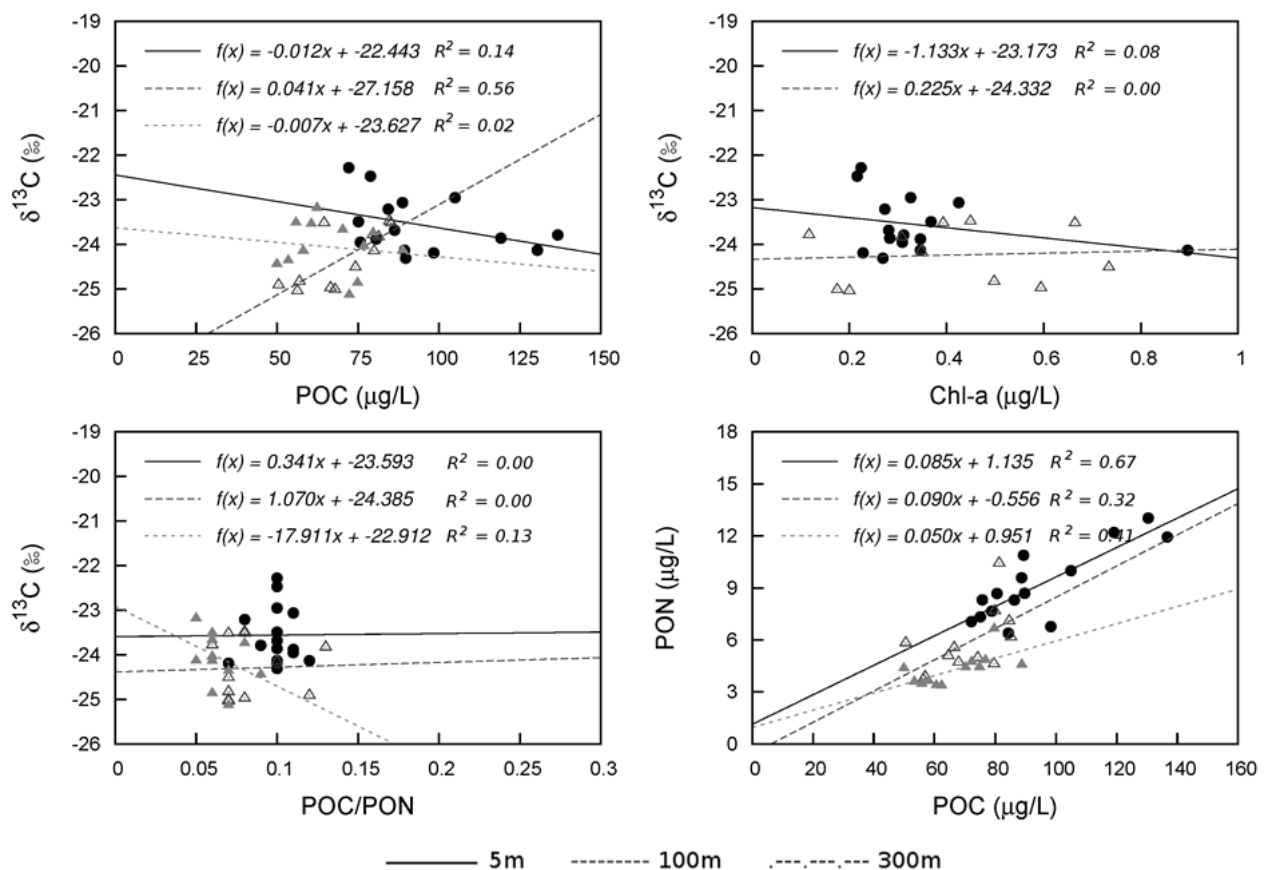

FIGURE 2. Profile δ^{13}C in correlation with: Particulate Organic Carbon (POC), chlorophyll-*a* and POC/Particulate Organic Nitrate (PON) quotient; POC against PON of all data from three depth (5, 100 and 300 m, respectively).

2, p-value = 0.0003146). The mean value of POC at 5, 100 and 300 m depths are 88.73 ± 20.20, 71.09 ± 11.91, and 66.32 ± 11.96 µg/L, respectively. These values are the same as 7835.7 ± 1683.1, 5887.0 ± 992.8, and 5576.5 ± 996.5 µmol/m^3, respectively. A similar result is shown by particulate organic nitrogen (PON), in that the values at 5, 100 and 300 m depths are significantly different (Kruskall Wallis rank sum test chi-squared = 25.35, df = 2, p-value=3.12 × 10^6). The mean value of PON at 5, 100 and 300 m depths are 8.68 ± 2.09, 5.32 ± 1.88, and 4.39 ± 0.93 µg/L, respectively. The concentration values at 5, 100 and 300 m depths are 651.6 ± 149.2, 415.1 ± 134.0, and 306.1 ± 66.3 µmol/m^3, respectively.

A molar ratio value of carbon and nitrogen (C:N mol ratio) of POM samples shows significant difference among the different depths (p-value < 0.01). Post hoc tests using Tukey contrasts (CI 95%) show that the C:N mol ratio of POM from depth 5 m < 100 m < 300 m (Table 2, Figure 2). The mean values are 12.19, 14.95 and 18.50, respectively. However, there is almost no significant linear correlation among POM variables as shown in Figure 2.

The nutrient profile varies among different depth and location. Both silicate and nitrate concentrations along the stations at 100 m depth are higher than at 5 m depth (Figure 3). The average value of silicate concentration at 5 and 100 m depth are 0.14 and 0.57 mg/L, respectively. The Wilcoxon signed rank test justify that both nitrate and silicate from 5 and 100 m depths are significantly different (p-value = 0.0001426 and 0.0001424, for NO_3 and SiO_3, respectively). The average nitrate concentrations are 0.07 and 0.32 mg/L for 5 and 100 m depth, respectively. Phosphate concentrations of surface water (5 m) along the stations are lower (average 0.01 mg/L) than the concentration at 100 m depths (average 0.04 mg/L). The average concentration of PO_4 from 5 and 10 m depths are significantly

different (Wilcoxon signed rank test p-value=0.0001417). A different trend is shown by the ammonium concentration, which is relatively similar between the 5 and 100 m depths (Figure 3). However, the statistical analysis suggested that the ammonium concentration from the different depths are significantly different (Wilcoxon signed rank test p-value = 0.0001345).

The value of δ^{13}C in the present study has a correlation with the POC, chl-a concentration and the water depth. The value of δ^{13}C tends to be varied and significantly different among the POM collected at different depths (One Way ANOVA p-value = 0.0117). The mean values of δ^{13}C are −23.56 ± 0.63, −24.29 ± 0.65 and −24.06 ± 0.58‰ for 5, 100 and 300 m depths, respectively. The POM tended to be isotopically lighter with increasing POC and chl-a, especially in the surface water at 5 m depths (Figures 2 and 4). However, the opposite trend is shown by the water from 100 m depths, the POM's δ^{13}C tended to be heavier follow the increase of POC. Furthermore, the value of POM's δ^{13}C in water surface tended to be heavier than the 100 and 300 m depths (Figure 4). The value of δ^{13}C at 300 m depths tended to decrease with the increasing of the POC/PON ratio (Figure 2). According to Figure 5, all POM collected at 5 m depths has a C/N ratio below 17, which is significantly
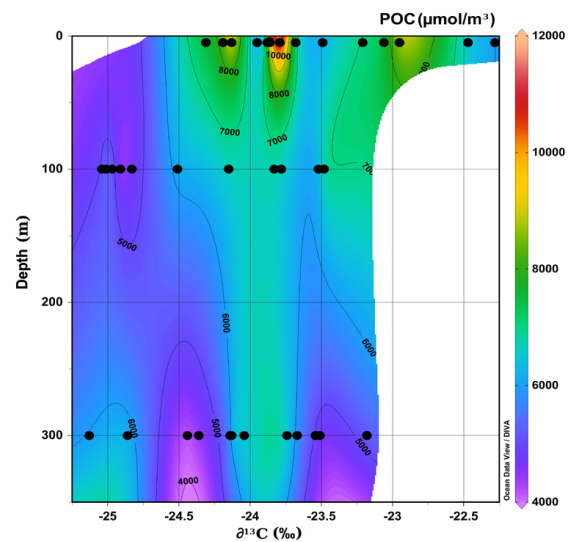
FIGURE 4. Isotopic profile of POM that shows depth- and POC-dependent.

FIGURE 5. Scatter plot of the δ^{13}C value of POM vs. C/N ratio at three depths. The modeled lines represent hypothetical mixing between terrigenous end-member (δ^{13}C = −24.2‰ and C/N ratio = 23) and marine end-members of different compositions. C/N ratio more than 20 is categorized as terrigenous end-member (Gilhooly et al. 2008).
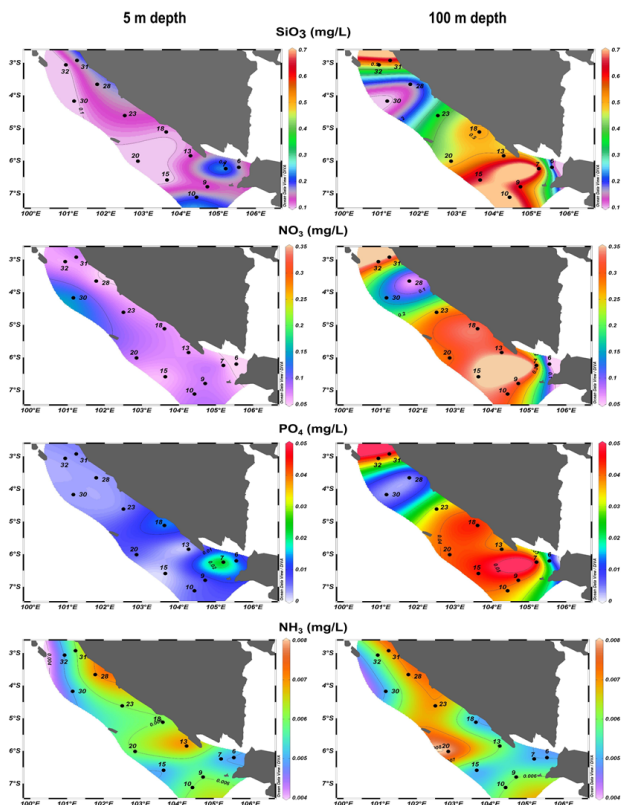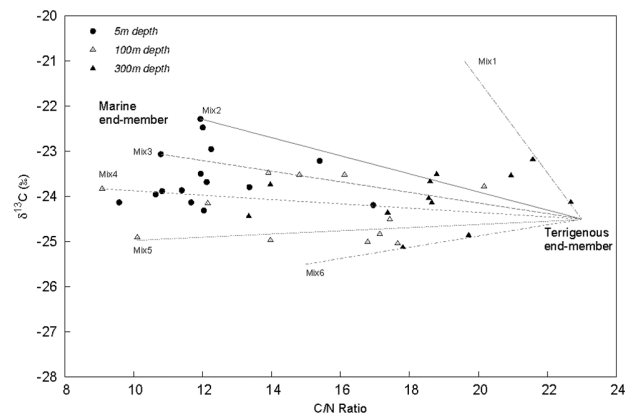

FIGURE 3. Spatial variability of silicate, nitrate, phosphate and ammonium from 5 m depth (left panel) and 100 m depth (right panel), respectively. The spatial distribution was generated using Ocean Data View.

Wahyudi et al.

TABLE 2. Statistical analysis of POM properties data.

Variable	Normality test ($a = 0.05$)			Test	Differentiation test according to the depth ($a = 0.05$)		Post-hoc test	Result	
	Test	Result			Result				
		p-value	Interpretation		p-value	Interpretation		CI	Interpretation
C/N-ratio	Shapiro-Wilk normality test	0.084	Normal distribution	100 m 300 m 5 m	2.22E-006	Significant difference in depth	Tukey contrasts	95%	All depth has different C:N mol ratio; 5 m < 100 m < 300 m
PON	Shapiro-Wilk normality test	0.007	Not normal distribution	a" "ab" "b	3.12E-006	Significant difference in depth; 5 m > 100 m > 300 m			
POC	Shapiro-Wilk normality test	0.004	Not normal distribution	Kruskal-Wallis rank sum test	3.15E-004	Significant difference in depth; 5 m > 100 m > 300 m			
Chl-a	Shapiro-Wilk normality test	0.004	Not normal distribution	Kruskal-Wallis rank sum test	0.3114	Insignificant difference; 5 m = 100 m			
δ^{13}C	Shapiro-Wilk normality test	0.393	Normal distribution	One-way ANOVA	0.0117	Significant difference in depth	Tukey contrasts	95%	100 m 300 m 5 m "a" "ab" "b

different compared to POM collected from the 100 and 300 m depths (One Way ANOVA p-value < 0.01; Tukey contrasts CI 95%).

4. DISCUSSION

4.1 Organic matter origin

Using the comparison between the C/N ratio versus δ^{13}C (Figure 5), we can predict the origin of the POM in the Southwestern Sumatran waters. Liu et al. (2007a) suggested that the POM is a mixture of marine and terrigenous origin organic matter. In this study we used representative values from all data collected, i.e. the lowest C/N ratio, the highest δ^{13}C value and others, to determine parameters for the terrigenous- and marine end-member origins (Figure 5). The terrigenous end-member is determined in this model (Figure 5) to have a C/N ratio of 23 and δ^{13}C value of –24.2‰ (different from Liu et al. (2007b) that used a C/N ratio of 22 and δ^{13}C value of –25.5‰). Typical C/N values for marine-end member is <6.6 (Martiny et al. 2014) and terrestrially-derived organic matters is >20 (Gilhooly et al. 2008). However, the marine end-member (both the C/N ratio and δ^{13}C) had various values, with mean values of 10.48 and –23.52‰ for the C/N ratio and the δ^{13}C, respectively. Kaiser et al. (2014) suggested that δ^{13}C values ranging from –24 to –17‰ are identical with the marine phytoplankton isotopic signatures.

The results suggest that POM collected at 300 m depth are composed of the terrigenous end-member materials, meanwhile POM collected at the 5 m depth are mainly composed of the marine end-member materials. However, POM collected in the 100 m depth were varied, i.e. some data shows that the POM is likely to be composed of marine end-member and the others are terrigenous end-member. This result suggests a similar trend found by a study of POM in the South China Sea, which suggested that POM collected from more than 400 m to 1200 m tended to be composed by terrigen (Liu et al. 2007a). Therefore, the gradation of POM major compositions from surface to the deep layer can be suggested as follows: 1) marine end-member in the surface layer (up to 100 m depth), which is possibly due to the high biomass of phytoplankton in the euphotic layer as shown by the chl-a concentrations, 2) mixed compositions at the upper part of the twilight zone (100 to 300 m depth), show that some of the terrigenous end-member may be composed of the freshly produced POM (Figure 6), 3) terrigenous end-member in the twilight zone (300 to 1000 m depth), 4) marine end-member in the deep layer (more than 1000 m; following Liu et al. (2007b)). However, this suggestion should be considered as the usual POM layers in the region when the upwelling is not occurring (April–May). Thus, when the upwelling occurs in the region (i.e. early August according to Susanto et al. (2001)), the profile could be different.

The twilight zone (100–1000 m depth) is considered to be the zone highly influenced by the biological pump, especially by the sinking of biogenic material, which is produced by plankton in the euphotic layer (Hirose et al. 2011). The variation of POM composition in the twilight zone can be driven by both the carbon biological pump (CBP) and microbial loop mechanisms. For instance, microbial organisms (bacteria, archaea, and viruses) can remineralize the POM, which respires back the carbon into carbon dioxide (Wassmann 1997; Sanders et al. 2014). This process occurs in the layer with minimal or no light (Arístegui et al. 2002), as in the twilight zone down to the deep layer.

These facts suggest that the marine end-member materials can be the major component of POM in the surface waters because these waters contain the euphotic zone with more marine planktonic organisms. The terrigenous mixed with marine end-member constitutes the POM in the twilight zone (up to 1000 m). Within this zone, the POM which is pumped to the deep from the surface layer may be degraded by microbes (Sanders et al. 2014). This process accompanied by the mixing of the terrigenous input makes the POM composition change. Also, within this zone, the production of fresh POM may occur (see the below section). Marine snow together with phytodetritus, fecal pellets and transparent exopolymer particles (TEP) may also be formed within the twilight zone (Turner 2015), further adding to the variables that determine the POM properties.
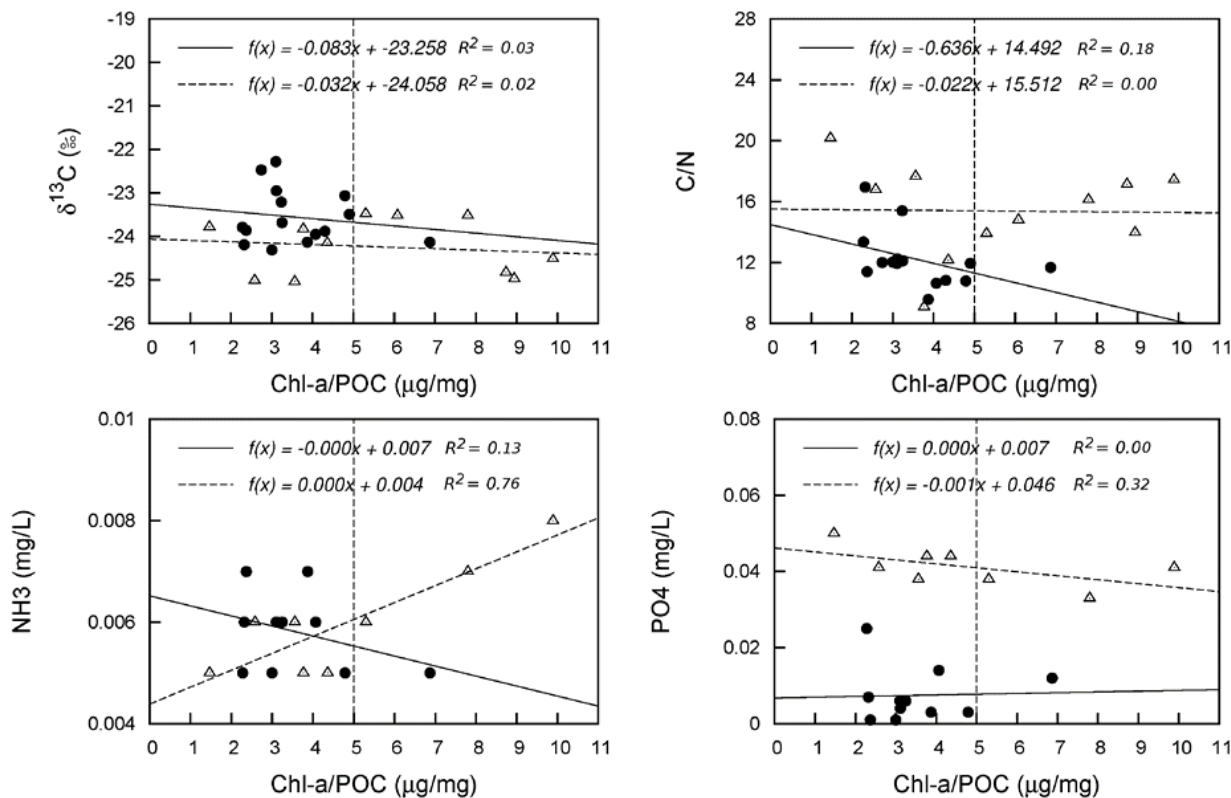
FIGURE 6. Properties of water samples and POM collected during E-WIN 2015 vs. the chl-a/POC ratio. Following Cifuentes et al. (1988) and Liu et al. (2007b) that samples with the chl-a/POC ratio above 5 µg.mg^{-1} are considered as containing high fraction of freshly produced POM. Filled circle and open triangular are samples from 5 m and 100 m depth, respectively.

4.2 Depth-dependent profile of POM's carbon isotope

The value of δ^{13}C tended to be various and significantly different among the POM collected at different depths. POM in the surface water tended to be isotopically lighter following the increase of POC and chl-a. POM's δ^{13}C tended to be heavier following the increase of POC in the water from depths of 100 m. However, the correlation is not considered significant enough (Figure 2). The surface layer was dominated by living planktonic organisms, that fractionation of ^{13}C is still at a minimum since they are primary producer (Post 2002).

Overall, the carbon stable isotope is heavier in the surface layer compared to the 100 or 300 m depth (Figure 5). The depth-dependent POM's carbon isotope may caused by the preferential fractionation of the carbon isotope as suggested by Liu et al. (2007b). Surface layer POM mainly composed by the phytoplankton (i.e. primary producer) that prefer using the lighter carbon isotope for its metabolism. Thus more heavier carbon then will be fractionated. Meanwhile, on the 100 or 300 m depth layer, living plankton may be decrease that cause same opportunity for lighter and heavier carbon isotope to be remineralized. The another possible factors could be the preferential remineralization of nitrogen rather than carbon. Letscher et al. (2015) suggested that in the case of dissolved organic matter, the order of the remineralization lifetimes of carbon is longer than nitrogen (C>N).

4.3 Autochthonous versus freshly produced POM

Autochthonous POM is determined as the POM that formed from the indigenous sources. The opposite is allochthonous, i.e. formed from the non-indigenous sources. All freshly produced POM should be autochthonous, how-

ever, not all autochthonous POM may be freshly produced (Liu et al. 2007b).

Freshly produced POM is one that is composed of the newly produced ^{13}C-enriched POC (Liu et al. 2007b). That is, the bulk of POM is newly aggregated. Following Cifuentes et al. (1988) and Liu et al. (2007b) samples with a chl-a/POC ratio above 5 µg.mg$_{-1}$ were considered as containing a high fraction of freshly produced/aggregated POM.

Half of the POM collected from 100 m depths were considered as freshly produced POM (Figure 6). The samples from 5m depths, however, showed a different tendency. This trend is different with the typical oceanic profile. In the twilight zone, some of the terrigenous end-member may be composed of freshly produced POM (Figure 6).

Although the POM in the surface water mass (5 m) was not considered as freshly produced POM (Figure 6), its main components are marine end-members, which means the POM is autochthonous. POM at the 100 and 300 m depths have a different profile. Only half of the 100 m depth POM are freshly produced, and almost all the POM at 300 m depths are freshly produced. According to Liu et al. (2007b), the freshly produced POM at 300 m depths can therefore be categorized as autochthonous although consist of mainly terrigenous end-member (Figure 5). Therefore, we can suggest that autochthonous POM may consist of marine or terrigenous end-member. We also suggest that the freshly produced POM may be composed of marine or terrigenous end-member.

4.4 Contribution of chl-a and nutrient on isotopic profile

Linear regression between the nutrients parameters and the δ^{13}C shows various trends (Figure 7). Nitrate and δ^{13}C have a significant relationship at α = 0.1, especially within samples collected from 5 m depth (p-value = 0.086, R^2 =
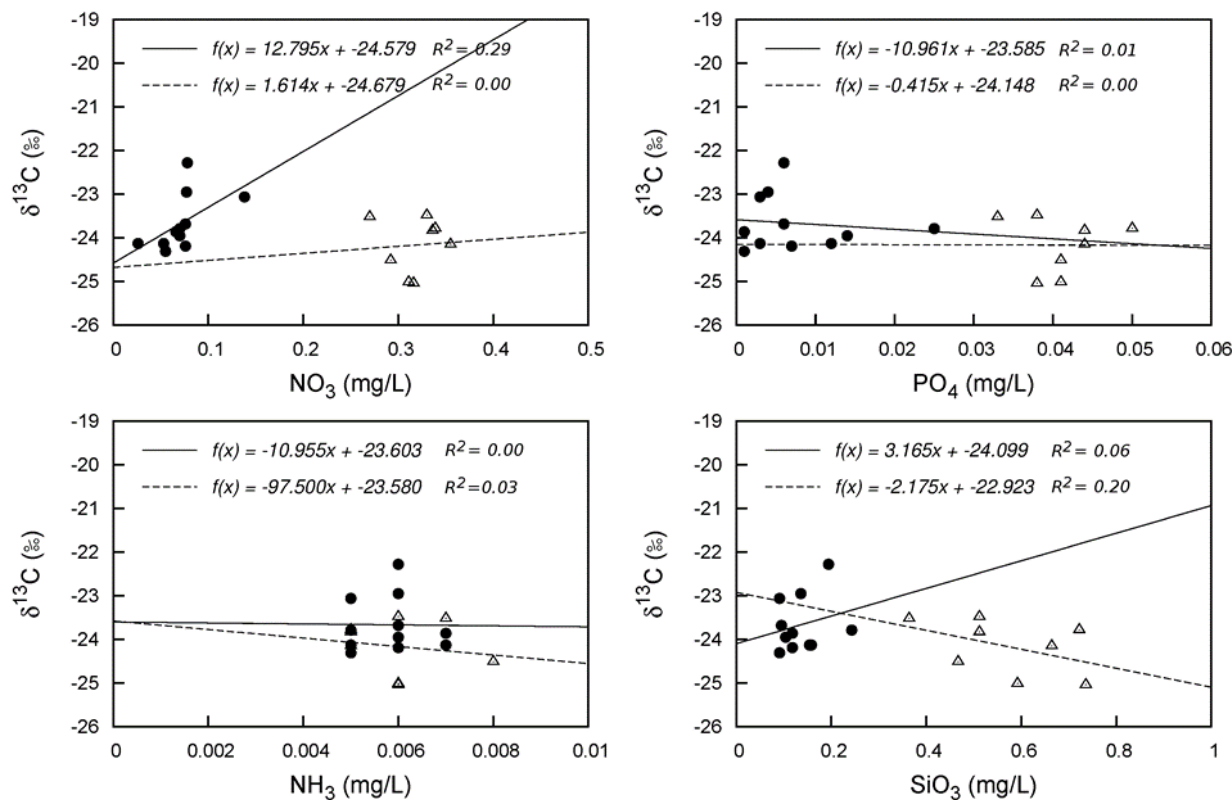
FIGURE 7. Correlation between nutrient parameters and isotopic profile of POM. Filled circles and open triangles are samples from 5 m and 100 m depth, respectively.

0.29). There is no significant correlation between nitrate and δ^{13}C collected from 100 m. There is a weak correlation shown by other nutrient parameters (silicate, phosphate, ammonium), with p-value > 0.05 (simple linear regression). However, we found that the general trend of our data is similar to Lara et al. (2010), i.e. the phosphate (5 and 100 m) and silicate (100 m) had a negative correlation with δ^{13}C. The same trend is shown by the ammonium (Figure 7), although the correlation is weak. Lara et al. (2010) suggested that ammonium, together with POC and sea surface temperature (SST) are independent variables that affected the δ^{13}C value, which explained the 83% δ^{13}C variance. On the other hand, nitrate has been suggested to be a variable that affects the δ^{15}N fractionation (Lara et al. (2010) and references therein).

As shown in Figure 2, POM tended to be isotopically lighter with increasing POC and chl-*a*, especially in the surface water at 5 m depth. However, the opposite trend is shown by water from 100 m depths; that is the POM's δ^{13}C tended to be heavier following the increase of POC. Chl-*a* and POC are the main proxy of phytoplankton, especially in terms of marine-end member POM (Liu et al. 2007a; Harmelin-Vivien et al. 2008). Lara et al. (2010) suggest that POM tends to be isotopically heavier with increasing phytoplankton biomass proxies such as POC, PON or chl-*a*. Our results show that this suggestion appears only in the depth below 100 m. Although the surface POM is considered to be the marine-end member, it is not freshly produced POM (see sections above). This is another explanation as to why POM collected in the surface layer of Southwestern Sumatra waters does not follow Lara et al. (2010)'s suggestion. Lara et al. (2010) suggest that the large range of δ^{13}C is related to phytoplankton metabolism and changes in species composition. This is considered as an adaptation to low nutrient concentrations. Since the nutrient concentra-

tions in the Southwestern Sumatran waters are high (see Figure 3), the range of δ^{13}C should not be large (i.e. –25.10 to –22.30‰), which is within our expectation.

5. CONCLUSION

The isotopic profile shows that the origin of POM in Southwestern Sumatran waters is as follows. The surface layer (up to 100 m depth) contains marine-end member POM. Mixed compositions of marine-end member and terrigenous-end member POM are found at the surface of the twilight zone (100 to 300 m depth). In the twilight zone (300 to 1000 m depth) the POM is terrigenous end-member and in the deep layer (more than 1000 m depth) the POM is marine end-member. The surface POM, as shown at 5m depth, is not freshly produced, so that POM tends to be isotopically lighter with increasing phytoplankton biomass proxies (i.e. POC or chl-*a*). The nutrients (i.e. ammonium, nitrate, and phosphate) also show a weak correlation in the isotopic profile of POM. However, the depth-dependent POM's carbon isotope may be caused by the preferential preservation of light carbon isotope, or the preferential remineralization of N rather than C. A temporal comparison study is still needed, especially during the upwelling that occurs annually in early August. Furthermore, the actual trend of the SSW of the recent years may be different with this study that conducted in 2015. However, our data obtained during this study may be used for validation on modelling biogeochemistry and oceanography.

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