Distribution of Humic Fluorescent Dissolved Organic Matter in Lake Shihwa: the Role of the Redox Condition

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Abstract

Hypoxia has occurred worldwide in coastal and marginal oceans. The redox condition has recently garnered major interest as a favorable condition for delivering sedimentary organic matter to the water column. In this study, we measured the fluorescence of fluorescent dissolved organic matter (FDOM) in brackish Lake Shihwa, Korea, in which hypoxic conditions are typically observed during summer. Especially, fluorescent intensities of the humic FDOM (FDOMH) were relatively high during summer, with a relatively lower dissolved oxygen (DO) level, and exponentially increased with decreasing DO concentrations. The results indicated that the production of FDOMH is associated with anaerobic processes. It was further supported by a significantly positive relationship between FDOMH and ammonium. Based on the relatively low values of redox potential (up to 60.0 mV) and high concentration of phosphate with the low DO level, this enrichment of FDOMH seems to be linked to the input of anoxic porewater. Using a simple schematic diagram, the contribution of FDOMH from reducing environments is comparable to that from stream water, which is known to be a major source in coastal regions. This study highlights that the redox condition is a key factor contributing to the production of FDOMH in coastal marine environments.

Keywords Fluorescent dissolved organic matter · Dissolved organic carbon · Lake Shihwa · Hypoxia · Dissolved oxygen · Redox condition

Introduction

Dissolved organic matter (DOM), generally represented as dissolved organic carbon (DOC), is well known as the most dominant reduced carbon form in marine environments (Carlson and Ducklow 1996; Shen and Benner 2018). DOC in the ocean is among the key parameters in the global carbon cycle because its total amount of carbon is equivalent to that in the atmosphere (Amon and Benner 1996; Carlson and Hansell 2015). A part of the DOC is optically sensitive and is known as colored dissolved organic matter (CDOM). Also, a fraction of CDOM emitting fluorescence by light absorption is recognized as fluorescent dissolved organic matter (FDOM). CDOM and FDOM effectively absorb ultraviolet and visible light and subsequently influence the light condition in the euphotic zone (Nelson and Siegel 2013; Siegel et al. 2005, 2002; Slonecker et al. 2016; Zepp et al. 2007). Thus, these are a key parameter controlling of biological production through attenuating photosynthetically active radiation (PAR) (Ferrari et al. 1996; Häder et al. 2007; Slonecker et al. 2016) or protecting labile species and corals from the harmful UV radiation (Arrigo and Brown 1996).

Although DOM in the ocean is mainly produced by in situ primary and secondary production and riverine input from terrestrial sources (Amon et al. 2003; Benner et al. 2005; Carlson and Hansell 2015), the redox condition in the ocean has recently been recognized as a key factor contributing to the preservation of and addition of organic matter into the ocean (Kim and Kim...
2016; Kowalczuk et al. 2015; Sexton et al. 2011). Sexton et al. (2011) reported that high concentrations of DOC in the Black Sea (120–200 μM) are derived from inactive mineralization owing to anoxic environments. Based on a laboratory experiment using a benthic chamber, the fluxes of sedimentary DOC and CDOM under a hypoxic condition, which is represented as less than 2.0 mg of O₂/L, were much higher than those under oxic conditions (Yang et al. 2014). Higher fluorescent intensities of refractory humic-like FDOM were observed in sediment porewaters under anoxic conditions rather than in sub-oxic or mixed redox sediments (Burdige et al. 2004). The FDOM fraction derived from anaerobic production in bottom sediments of the deep East Sea (Sea of Japan) accounted for approximately 10% of the total production in the deep water column (Kim and Kim 2016). In addition, the excess of sedimentary FDOM can be transported to overlying water by reductive dissolution of coprecipitated FDOM and iron oxides (e.g., FeOOH) in the anoxic condition (Skoog et al. 1996). Thus, the redox condition of the water, as well as sediments, can influence the distribution of DOM and associated ecological aspects in coastal and open oceans.

Unfortunately, anoxic and hypoxic environments continuously occur in global coastal oceans (Diaz and Rosenberg 2008). Lake Shihwa is a representative enclosed artificial brackish lake on the western coast of Korea (Fig. 1). After the construction of the tidal barrage in 1994, hypoxia is usually observed during summer due to the restriction of water circulation (Kim and Kim 2014; Lee et al. 2014a, 2018). The dissolved oxygen (DO) level starts to decrease with increasing water temperature in May. Then, the hypoxic bottom-water appears usually in June, and it persists until September (Lee et al. 2018). In addition, the large amounts of organic matter are transported through the six streams and creeks around the lake (Lee et al. 2017, 2014b). All of streams and creeks are quite small (less than 10 km long each) and total discharge rate is ca. 3.4 × 10⁸ m³/year. Thus, Lake Shihwa is an ideal study area to determine the response of organic matter behavior depending on the redox condition. Here, we investigated the seasonal variations in the FDOM distribution with ammonium (NH₄⁺), phosphate (PO₄³⁻), DO level, and an Eh-pH diagram of natural waters in Lake Shihwa, which is considered a representative reduction environment subject to a seasonal dynamic transition in the redox condition.

**Materials and Methods**

**Sampling and Measurement of Hydrological Properties**

Sampling campaigns to investigate DOC, FDOM, nutrients, and hydrologic properties (temperature, salinity, DO, pH, and
Water continued to overflow (Kim and Kim 2014). The concentration of DO measured using a portable sensor was closely correlated with that using Winkler titration (\([\text{DO}_{\text{Orion}}] = 1.012 \times [\text{DO}_{\text{Titration}}] - 0.346; r^2 = 1.00; p < 0.001; n = 57\)).

**Analysis of DOC**

Samples for DOC were vacuum filtered using pre-combusted Whatman GF/F filters within 1 h of sample collection. To prevent microbial activity, the filtered samples were acidified using 6 M HCl, followed by hermetic sealing in pre-combusted (500 °C for at least 4 h) 20-mL glass ampoules (Wheaton Scientific, Millville, NJ). The concentration of DOC was measured using a TOC analyzer (TOC-VCPh, Shimadzu, Japan). In order to analyze with high accuracy, the system blank was reduced until the signal from the DOC-free distilled water (DIW) was stable within the limit of detection (<5 μM). The accuracy of the DOC concentration was verified every day using deep-sea reference (DSR 41–44 μM, University of Miami) samples. Our DSR measurement results were in good agreement with the DSR values (within 2%).

**Analysis of FDOM**

Samples for FDOM were filtered using GF/F filters, along with the DOC samples and re-filtered using polycarbonate filters (with a pore size of 0.2 μm). The samples were stored in pre-combusted dark amber bottles to avoid photodegradation and remained in a refrigerator at 4 °C until analysis. Just prior to measurement, the seawater samples were allowed to stand in a dark chamber to approach room temperature. Three-dimensional fluorescence spectroscopy was performed using a spectrofluorometer (FS-2, SCINCO, Korea) within 1 week of sample collection. Excitation–emission matrix (EEM) fluorescence spectroscopy analysis was conducted using scanning emission wavelengths of 250–600 nm at 2-nm intervals and excitation wavelengths of 250–500 nm at 5-nm intervals. Fluorescent intensities of the samples were normalized daily to those of a quinine sulfate dihydrate standard solution in 0.1 N sulfuric acid, and these values were expressed as quinine sulfate units (QSUs). Rayleigh and Raman scattering peaks were eliminated and replaced by three-dimensional Delaunay interpolation of the remaining data (Zepp et al. 2004). Parallel factor analysis (PARAFAC) modeling for the compilation of 273 EEM data from three sampling campaigns was performed in the MATLAB R2016a program using the DOMFluor toolbox (Stedmon and Bro 2008). The precision of the FDOM measurement was ±0.01 QSU, and the limit of detection was 0.14 QSU (Kim and Kim 2016).

**Analysis of Inorganic Nutrients**

Samples for inorganic nutrients (nitrate, nitrite, and ammonium) were vacuum filtered simultaneously with the DOM samples. The filtered samples were transferred to acid-clean polypropylene Nalgene bottles and stored in a freezer. The concentration of the inorganic nutrients was photometrically measured from duplicate samples using an auto nutrient analyzer (QuAAtro39, SEAL Analytical, UK). The accuracy of nitrate concentration was verified every day using two different certified reference materials (CRMs): MOOS-3 (23.0 ± 0.3 μM, National Research Council of Canada) and RMNS (30.88 ± 0.24 μM, KANSO, Japan). Our CRM measurement results were in good agreement with the certified values (within 5%). The detection limits of NOx (nitrate + nitrite), ammonium, and phosphate were 0.01 μM, 0.01 μM, and 0.05 μM, respectively (3 × the standard deviation of the blank value, Brügmann and Kremling (2007)). The concentrations of nutrients were measured with a precision of <5% based on the repeated measurement of CRM.

**Statistical Analyses**

Statistical analyses were carried out using IBM SPSS version 23 for Windows (Chicago, IL, USA). Correlation between variables was analyzed with the Pearson correlation.

**Results and Discussion**

**Hydrological Properties in Lake Shihwa**

Based on the sectional distributions of the hydrological properties in Lake Shihwa, a relatively strong density gradient was observed during August 2016 (16.42 to 19.22 kg/m³), particularly within the upstream stations of the lake, compared to that during October 2015 (21.66 to 22.20 kg/m³) and March 2016 (23.03 to 25.02 kg/m³) (Table 1; Fig. 2). The relatively cold and saline seawater appeared from stations 1...
to 5 (Fig. 2), indicating that seawater can transport into the central lake after opening the water gate of the dike. However, the water mass in the shallow upstream stations of the lake seemed to be commonly stagnant. The thermocline was observed within 1-m depth.

The concentrations of DO ranged from 4.70–8.39 mg/L (average 6.40 ± 0.98 mg/L), 7.33–12.1 mg/L (average 9.17 ± 1.17 mg/L), and 3.20–5.88 mg/L (average 4.89 ± 0.58 mg/L) during October 2015, March 2016, and August 2016, respectively (Table 1; Fig. 2). Based on the sectional distribution of water density and temperature (Fig. 2), the higher concentrations of DO during October 2015 and March 2016 seem to be attributable to the active circulation and low water temperature. However, the relatively low concentrations of DO during August 2016 particularly in the upstream stations of the lake, are likely associated with the limited vertical water mixing by a steep vertical gradient of water density.

**PARAFAC Components**

The PARAFAC model identified three components from the EEM data of Lake Shihwa and was statistically validated using the split-half validation (Fig. S1). According to the peak locations of each component, two humic-like components (C1 and C2) and one protein-like component (C3) were identified. C1 (Maxex/em = 325/428 nm) was red-shifted FDOMH that has been traditionally documented to be a humic-like component originating from a terrestrial environment (Osburn et al. 2011; Stedmon and Markager 2005; Stedmon et al. 2003; Walker et al. 2009). The wavelength location of C1 is similar to that of humic organic matter (Maxex/em = 320/420 nm) which has been usually used to represent the concentration of humic organic matter (Chen and Bada 1992; Fujita et al. 2010; Hayase and Shinozuka 1995; Yamashita et al. 2007). C2 (Maxex/em = 300/356 nm) was blue-shifted FDOMH that was categorized as a humic-like component produced by microbial activity in the water column (Coble 1996; Osburn et al. 2011; Walker et al. 2013). C3 (Maxex/em = 280/332 nm) was associated with the tryptophan-like component, which is produced by biological production in the ocean (Yamashita et al. 2017; Yamashita and Tanoue 2003). These components were also found in lake environments in other countries (Bittar et al. 2015; Borisover et al. 2009; Zhang et al. 2009; Zhou et al. 2018, 2016) and in Lake Shihwa (Phong et al. 2014).

**Distributions of FDOM in the Lake**

The fluorescent intensities of all components were found to be higher in the upstream stations of the lake (stations 5–8) relative to the downstream stations of the lake (stations 1–4) (Fig. 2). In addition, the high fluorescence generally showed in the subsurface layer. The fluorescent intensities of C1 were negatively correlated with salinity ($r^2 = 0.30, p < 0.001$) (Fig. 3a), indicating that C1 seems to be a result of input of freshwater into Lake Shihwa. In this region, the potential freshwater sources are small streams and precipitation. However, FDOMH derived from precipitation is unlikely because all sampling campaigns were conducted at least 2 weeks after heavy precipitation. Lee et al. (2017) reported that the organic matter originates from the industrial complexes area, wetland, and urban area through the surrounding creeks, although they did not account for the bottom-sediment source. Thus, the freshwater-driven C1 was mainly supported by the streams around the lake. The scattered data of the relationship between C1 and salinity may be attributed from in situ production and benthic sources. Here, the relationships between C1 and salinity during October 2015 ($r^2 = 0.30, p < 0.001$) and March 2016 ($r^2 = 0.30, p < 0.001$) were statistically less significant than during August 2016 ($r^2 = 0.71, p < 0.001$). These results might be because of the relatively low contribution of freshwater during October and March compared to that during August. This is supported by the higher rainfall during August 2016 (~143 mm/month) compared to that during October 2015 (~48 mm/month) and March 2016 (~37 mm/month) (www.kma.go.kr). On the other hand, the relationships of C2 and C3 against salinity were less statistically significant ($r^2 = 0.11, p < 0.001$ for C2; $r^2 = 0.04, p = 0.008$ for C3) (Fig. 3c, e), indicating that the production of C2 and C3 was attributed from various processes rather than fresh sources.

C1 was generally observed to exponentially increase with a decrease in the DO level ($r^2 = 0.70$ for C1; Fig. 3b), particularly during August 2016. It is reasonable to determine that the production of C1 is likely to be associated with the anaerobic processes. However, the scatterplots of C2 and C3 against the DO level were inconclusive results (Fig. 3d, f). During March 2016, an increase in C1 was also observed below the surface layer (~1 m) of the upstream stations of the lake (Figs. 2 and 3b), perhaps owing to microbial production of marine organic matter based on the excessive fluorescence of C2 relative to C1 (Fig. 3d). In the previous studies, the

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**Table 1** Summary of water temperature, salinity, water density, and DO level in Lake Shihwa during three sampling campaigns

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Salinity</th>
<th>Water density (km/m³)</th>
<th>DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 2015</td>
<td>19.30–21.48 (avg. 20.60 ± 0.62)</td>
<td>30.00–31.85 (avg. 31.55 ± 0.45)</td>
<td>21.66–22.20 (avg. 22.07 ± 0.10)</td>
<td>4.70–8.39 (avg. 6.40 ± 0.98)</td>
</tr>
<tr>
<td>March 2016</td>
<td>30.69–31.87 (avg. 31.64 ± 0.19)</td>
<td>27.64–31.45 (avg. 28.59 ± 1.06)</td>
<td>23.03–25.02 (avg. 24.66 ± 0.52)</td>
<td>7.33–12.1 (avg. 9.17 ± 1.17)</td>
</tr>
<tr>
<td>August 2016</td>
<td>6.33–10.11 (avg. 7.44 ± 1.25)</td>
<td>28.57–30.65 (avg. 30.40 ± 0.36)</td>
<td>16.42–19.22 (avg. 18.75 ± 0.60)</td>
<td>3.20–5.88 (avg. 4.89 ± 0.58)</td>
</tr>
</tbody>
</table>
anaerobic activity is suggested as a source of FDOM in the marine environments. Chen and Bada (1994) suggested that sedimentary FDOM is produced by diagenesis of organic matter in anoxic sediment. In addition, the production of FDOM is associated with the redox condition in the water column and bottom sediment based on a benthic chamber experiment (Yang et al. 2014) and the vertical profile of FDOM in porewater (Burdige et al. 2004). Kim and Kim (2016) reported that in situ diagenetic transformation of sedimentary organic matter in anoxic sediment produces FDOM, and this contributes to excess FDOM in the water column. In this study, we used C1 as the representative FDOM in order to determine the anaerobic FDOM production and compare with the fresh water-driven source in the lake.

**Anaerobic Sources of Humic-like FDOM**

In this study, the anaerobic production of FDOM was supported by a significant correlation of C1 against ammonium \( (r^2 = 0.60, p < 0.001) \) and phosphate \( (r^2 = 0.66, p < 0.001) \) (Fig. 4). Ammonium is generally produced by the anaerobic microbial decomposition of organic matter from dead organisms under an anoxic condition: the process is termed ammonification (Herbert 1999). However, we did not observe hypoxia in the lake water during the three sampling campaigns. In general, the DO level in bottom sediment is completely depleted within a few centimeters of the bottom sediment (Cai and Sayles 1996). Thus, anaerobic production of FDOM and ammonium seems to occur in the bottom sediment, and then, it is transported to the overlying water column. In addition, the ratio between ammonium and NOx was significantly higher during August 2016 than that during March 2016, indicating that denitrification may have occurred because of the lower DO level during August 2016 in this lake (Fig. S2). The high concentrations of phosphate in the upstream stations of the lake were observed in August 2016. Because phosphate is accompanied by the flux of sedimentary organic matter under an anoxic condition (Lai and Lam 2008; Moore et al. 1998;...
Søndergaard et al. 2003; Skoog et al. 1996; Skoog and Arias-Esquível 2009), the enrichment of phosphate seems to be further evidence to support anaerobic source from bottom sediment of Lake Shihwa.

In the scatterplot of C1 against salinity, the data for the samples near the water gate during August 2016 (e.g., with the highest salinity) was on the slope of the relationship for the surface water during March 2016 (Fig. 5). These results may indicate that the distribution of FDOM derived from mixing between stream water and seawater was consistent during March and August 2016. A linear mixing line may indicate that the photodegradation of surface FDOM was negligible. It is probably related to the estuarine and river-dominated region (Guo et al. 2007; Osburn et al. 2009). Owing to the relatively high enrichment of C1 to C3 in the low DO level (Fig. 3), we speculated that the scatterplot above the surface trend during March 2016 is influenced by other sources, such as the benthic flux from the reduced sediment. In order to eliminate the influence of freshwater-driven FDOM, the fluorescent intensities of C1 were normalized to a constant salinity of 32, which is the maximum salinity in front of the water gate. The salinity-normalized FDOM (nFDOM) was calculated using the non-zero end-member for freshwater (FDOMfresh) based on the relationship between FDOM and salinity. The equation is shown as follows:

$$n_{\text {FDOM}} = \frac{F_{\text {DOM}} - F_{\text {DOM}_{\text {fresh}}}}{S} \times S_{\text {sea}} + F_{\text {DOM}_{\text {fresh}}}$$

where FDOM, S, and Ssea denote the measured fluorescent intensity of FDOM, salinity, and the reference salinity for the
seawater (32), respectively. FDOM}_{fresh} denotes the end-member of FDOM}_{H} in the freshwater. It was derived from the intercept value (38.0 QSU) of the relationship between C1 and salinity in the surface lake water during March 2016 ([C1] = −1.10 × [salinity] + 38.0, \( r^2 = 0.80, p < 0.001 \)), which seems to have no influence on anaerobic FDOM}_{H} production from bottom sediments (Fig. 5). The nFDOM}_{H} was dependent on the DO during August 2016 (\( r^2 = 0.65; p < 0.001 \)), whereas the relationships between the nFDOM}_{H} and DO were insignificant during October 2015 (\( r^2 = 0.20; p = 0.203 \)) and March 2016 (\( r^2 = 0.03; p = 0.203 \)) (Fig. S3). Anaerobic production can be a significant source of FDOM}_{H} in a lake environment with low concentrations of DO.

Based on a redox potential (Eh)-pH diagram of natural water (Brookins 1988; Brown 2005; Garrels 1960; Hem 1985), the sources of the enriched FDOM}_{H} during summer seemed to be the reduced condition and also porewater or groundwater in the natural environment. Only during summer were very low Eh values (60.0–281.6 mV; average 249.3 ± 39.7 mV) observed with a nearly constant pH value of ~8.3, particularly in the shallow upstream stations of the lake (Fig. 6). These results indicate the input of water from the reduced environments, such as anoxic porewater (Hem 1985). During October 2015, the distributions of the plot showed a relatively large scatter and a low limit value of Eh (approximately ~300 mV), perhaps because of the active physical mixing of the water masses during a cold and windy season. During March, the Eh and pH values corresponded to those of the normal seawater.

**Contributions of Various FDOM}_{H} Sources to Its Distribution**

The contribution of various sources to the FDOM}_{H} budget in the upstream stations of the lake (stations 5–8) was evaluated using a simple schematic diagram (Fig. 5). We assumed that the distribution of FDOM}_{H} in the lake is potentially affected by two external sources: stream water and reducing bottom sediment in the lake. The lowest concentrations of C1 at the water gate are considered to be the background concentration derived from the coastal seawater (2.82 QSU). The linear mixing trend assumed a rapid mixing between stream water and seawater without external factors. Thus, the increased C1 concentration due to the stream-origin FDOM}_{H} was calculated as the difference between an estimated concentration using the C1-salinity equation and the background concentration, and it averaged 0.96 ± 0.60 QSU and 2.05 ± 0.55 QSU during

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**Fig. 4** Scatterplots of C1 against ammonium (a) and phosphate (b). The data in the parentheses indicate the sample affected by resuspended bottom sediment.

**Fig. 5** A schematic diagram illustrating the potential FDOM sources (seawater, stream water, and reducing environments) contributing to the distribution of FDOM. The triangle marks and the dotted line indicate the data and the relationship between C1 and salinity in the surface lake water during March 2016. The data in the parentheses indicate the sample affected by resuspended bottom sediment.
March and August 2016, respectively. The higher concentration during August 2016 may be attributed to the summer monsoon. The additional FDOMH input from the reducing bottom sediment was shown by scatterplots above the linear mixing line. The C1 concentration derived from the additional source was calculated as the difference between the measured concentration and an estimated concentration using the C1-salinity equation. The input of FDOMH from the reducing sources seemed to result in an increase of $0.62 \pm 1.21$ QSU and $1.81 \pm 1.64$ QSU during March and August 2016, respectively. The concentrations of this FDOM source were comparable to those from the stream water (two-tailed Student’s $t$ test; $p = 0.32$ for March 2016 and 0.40 for August 2016). Therefore, the FDOM input from the reducing environments seems to be important in significantly enhancing the FDOM abundance in the coastal brackish lake. In October 2015, the fluorescent intensity of FDOM$_H$ showed no correlation with salinity and DO level, perhaps due to the mixing effect. Thus, we cannot distinguish the contribution from the river and reducing sources in October 2015.

**Potential Driving Mechanism**

During October 2015, the cold and windy atmospheric conditions resulted in strong physical water mixing, and subsequently a high DO level in the lake water (Fig. 7). During March 2016, the high concentration of DO seemed to be attributed to the high DO solubility because of the low water temperature. A relatively low oxygen concentration was found during August, particularly in the shallow upstream stations of the lake (Fig. 2) although hypoxia was not observed during August 2016. However, hypoxia annually occurs during the summer season in Lake Shihwa (Lee et al. 2018). The stagnant water resulting from the strong thermocline and the construction of the water reservoir decelerates the physical water mixing rate. In addition, the high input of organic matter and electron acceptors from streams accelerate oxygen consumption to degrade organic matter (Lee et al. 2014a). The decrease in the DO level induces (1) weakening of the oxygenated layer, preventing the diffusion of the sedimentary DOM; (2) inactive remineralization in the water column; and (3) accumulation of terrestrial FDOMH in the lake water during summer. Particularly, the proportion of FDOM to DOC was observed to increase with decreasing DO (Fig. S4), suggesting that a light-absorbing fraction of DOM is preferentially provided by anaerobic production. The abundance of FDOM in the surface water may reduce penetration of sunlight, which is an essential factor controlling biological activities (Ferrari et al. 1996; Häder et al. 2007; Retamal et al. 2008; Slonecker et al. 2016), and it subsequently decreases in photosynthetic oxygen evolution rate. At this time, a large amount of sedimentary organic matter in the water column may accelerate the possibility of hypoxia (Su et al. 2017). This positive feedback of the DO level causing an additional organic matter source seems to endanger...
the coastal ecosystem. Unfortunately, Diaz and Rosenberg (2008) reported that the number of hypoxia events has approximately doubled each decade since the 1960s. This might be attributed to human activities, such as the construction of a dike for the land reclamation project and sewage contamination. Thus, the redox condition depending on the concentration of DO should be more important as a key factor to control the distribution of DOM in the future.

Conclusions

Based on a significant negative correlation between C1 and salinity, FDOMH in Lake Shihwa generally originates from streams. In addition, based on an exponentially negative correlation of C1 against DO, FDOMH in Lake Shihwa was found to be produced by anaerobic processes, particularly in bottom sediments. Anaerobic production of sedimentary FDOMH is further supported by the close relationship of C1 against NH4+, PO43−, relatively higher NH4+/NOx ratios, and very low Eh values in the enriched FDOMH samples. The contribution of FDOMH fluorescence originating from the reducing environments was found to be comparable to the stream-driven FDOMH in the lake. Thus, this study highlights that the anaerobic process in the bottom sediment, as well as the stream-driven FDOMH, seems to be among the main sources of FDOMH and the redox condition may be a key factor contributing to the distribution of organic matter in this coastal environment. Further extensive studies are necessary to quantify the fluxes of the sedimentary FDOM produced by anaerobic microbial activities, and their subsequent ecological influence on the ocean.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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